TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Materials and Environmental Technology

AIR PERMEABILITY PROPERTIES OF CROSS LAMINATED TIMBER EXTERNAL WALL

RISTKIHTLIIMPUIDUST VÄLISSEINTE ÕHUPIDAVUSE OMADUSED

MASTER´S THESIS

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Tallinn, 2019

AUTHOR'S DECLARATION

Hereby I declare, that I have written this master's thesis independently.
No academic degree has been submitted based on this material. All works, major viewpoints and data are of my original investigation and others of the other authors used in this master's thesis have been referenced.

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THESIS TASK

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Study programme: KVEM- Technology of Wood and Plastic

Main speciality: Wood Technology

Supervisor: Early stage researcher, Villu Kukk

Co-supervisor: Head of the Laboratory of Wood Technology, Professor Jaan Kers

Thesis topic:

(in English) Air permeability properties of cross laminated timber external wall

(in Estonian) Ristkihtliimpuidust välisseinte õhupidavuse omadused

Thesis main objectives:

1.Determine the effect of initial moisture content on CLT external walls

2.Determine the effect of insulation on CLT external walls

3.Determine the effect of indoor environment on CLT external walls

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Preparing and installing specimens in test wall location	01/2018
2.	Carrying out air permeability measurements on all test wall samples	03/2019
3.	Collecting and analysing data	04/2019
4.	Writing and submission of thesis	05/2019

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TABLE OF CONTENTS

PREFACE

This thesis was initiated by Villu Kukk who is the project supervisor of the author. Villu Kukk who is an early stage researcher has been working on air permeability properties of cross laminated timber (CLT) for over five years and already has so many publications in this field under his name. The current study was carried out in the TTU nZEB (nearly zero energy buildings) technological test facility.

Air permeability test was carried out on 12 test walls in this research with CLT as the airtight layer. The differences in the test walls are the initial moisture content (MC) in the CLT panels and the insulation material present in each test walls. All the test walls had gone through the four seasons of the Estonian weather condition before the first set of air permeability measurement. Result obtained showed that both indoor atmospheric condition and initial MC in CLT panel had an effect on the air permeability properties of test walls with initial MC seen to having the biggest impact. The effect of insulation could not be verified as results obtained were not sufficient enough.

A whole lot of efforts from colleagues went into actualizing this research. I would like to recognize the help of Laura Cukkere, also a master's student working on a different topic with the same test wall specimen of this research. She gave her best and because of her contribution, this research was a success. In quick succession, I would also like to thank the staffs of the Technology of wood and plastics which includes Heikko Kallakas, Triinu Poltimae, Karmo Kiiman, Ahto Reiska just to name a few. They really played a pivot role in achieving the practical objectives of this project and for that I show my appreciation.

I would also like to thank my supervisors (Villu Kukk and Prof. Jaan Kers) for their guidance and advice during the whole two years of the program. Without them, it would have been more unless impossible to obtain all the results of this master's thesis.

Keywords: CLT, air permeability, moisture dry-out, CLT wall, Master's thesis

List of abbreviations and symbols

Abbreviations

1K-PUR - One-component polyurethane adhesives

ANSI - American National Standards Institute

APA - The Engineered Wood Association

CLT - Cross laminated timber

PF - Phenol formaldehyde

EPI - Emulsion-polymer-isocyanate adhesive

MC - Moisture content

EMC - Equilibrium moisture content

RH - Relative Humidity

Symbols

ka - Air permeability	[kg/Pa s·m]
Δp - Air pressure difference	Pa
U - Thermal transmittance	W/ (m2K).
q50 – Air leakage rate	m^3/ (m^2*h)
$\dot{V}$- Air flow rate	m^3/ (m^2*h)
T – Temperature	ºC

1 INTRODUCTION

Materials generally used for construction purpose are expected to comply with certain requirements reaching far beyond the current expectation. New construction materials are not only expected to be more durable and exhibit a longer life, but, should be more ecologically friendly when compared with conventional materials. One promising product, satisfying the criteria of both environmentally friendly, sustainability and also satisfies the current expectation of service performance is cross laminated timbers (CLT) (Sikora, McPolin and Harte, 2016).

CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been massively utilized in residential and non-residential applications in Europe. There are currently over one hundred CLT projects in Europe. In the mid-1990s, Austria undertook a joint research academical effort that culminated in the development of modern CLT. In the early 2000s, construction with CLT became prominent due to the green building movement which is assumed to improve the health of the environment. Other reasons apart from the environmental benefits includes good strength to density ratio, quicker installation reducing the cost of construction, waste reduction, design versatility and better thermal performance. (Gagnon Sylvain et al, 2013).

In Europe, the use of CLT panels as a building material has increased over the past years. The awareness is growing and different researches are being carried out to investigate its suitability in the construction industry. Around the world, a large numbers of impressive buildings and different structural edifice has shown several advantages this material can offer in the construction industry. Because of the extensive use of CLT in Europe, the material is becoming more competitive most especially in tall buildings (e.g 5 to 8 stories), which is a key advantage. Other structural advantages include good insulation and good performance under fire because of its mass wood structure, good thermal insulation, ease of flexibility in design and its hybrid nature opportunity as it can be used with other construction material.(Gagnon Sylvain et al, 2013).

Proper standards for CLT designs design only became available until the beginning of the decade. One of such standard is the ANSI/APA PRG 320 Standard (2011) for Performance-Rated Cross Laminated Timber by cooperation of American National Standards Institute (ANSI) and The Engineered Wood Association (APA) which is valid for both U.S. and Canada. This was the first standard for CLT panel as a construction material (Yeh *et al.*, 2012). In Europe, EN 14080 “Timber structures - Glued laminated timber and glued solid timber – Requirements” was the first standard used for CLT panel design production and not until 2015 when EN 16351 “Timber structures - Cross laminated timber – Requirements” was developed. EN (16351, 2015) was developed from EN 14080 and was made for producing requirements for two kinds of CLT products: cross laminated timber as X-Lam and cross laminated timber as X-Lam with large finger joints (EVS-EN 16351, 2015).

1.1 CLT as a product

CLT as a timber structure can be described as "structural timber consisting of at least three layers of which a minimum of three are orthogonally bonded, with at least two of the layers comprising of timber", in other words every layer of panel is placed cross-wise to the next layer, hence the name CLT (EVS-EN 16351, 2015). This specific orientation of each layer results in homogenizing of swelling and shrinking behaviour associated with wood, excellent strength, rigidity, and stability characteristics which tends to amplify its load bearing abilities. The degree of anisotropy in wood along different directions and the influence of natural variations, such as knots, are reduced in comparison with construction timber (Brandner *et al.*, 2016). Construction and project delivery time are easily reduced because load-bearing CLT wall and floor panels can be easily assembled on site to form multi-storey buildings thereby reducing costs, and maximizing efficiency at all stages of construction.

Cross laminated timber (CLT) is a development from the long known glue laminated timbers. Crossing of the boards in each layer of CLT panel (Figure 1.1) enhances the stability of wood as a construction material. This helps to reduce the shrinkage and swelling challenges associated with wood due to his anisotropic nature. In Europe, usage of CLT as a constructions material is increasingly but its demand is still considered to be low when compared to other construction materials, this could be as a result of lack of knowledge and design details (Skogstad, Gullbrekken and Nore, 2011)

1.1.1 CLT composition

Cross-laminated timber (CLT) is an engineered wood panel consisting of three, five, or seven layers of dimensioned lumber crossed at right angles to one another. Glue in form of adhesives are used to join the lumbers to one another thereby forming a structural panel that is strong, rigid, and dimensionally stable. Since CLT panels are generally considered to resist high racking and compressive forces, this makes them to be a cost effective material for storey buildings and very long span structures. CLT can be used interchangeably with other wood products and also in hybrid applications, which is why it is seen both as a product and a system.

The main composition for CLT panels includes majorly structural lumber and adhesives and sometimes nails. According to EN (16351, 2015), the thickness of CLT shall not exceed 508 mm. Dimension tolerances permitted at the time of manufacturing includes a thickness of ± 1.6mm or 2% of the CLT thickness, width of + (3.2mm of the CLT width and a length of ± 6.4mm of the CLT length. Lumber can be made mainly from softwood species such as Norway spruce (*Piciea abies*), Fir (*Abies Alba*), Scots pine redwood (*Pinus sylvestris*) etc. The adhesive systems which are allowed for use in CLT production according to EVS-EN (16351, 2015) are phenoplast- and aminoplast-adhesives which include adhesives phenol formaldehyde (PF), one-component polyurethane adhesives (1K-PUR) and Emulsion-polymer-isocyanate adhesive (EPI). It is to be of note that 1K-PUR was the main adhesives used in this research.

Figure 1.1: Five layered CLT panel (Kramer, Barbosa and Sinha, 2013)

1.1.2 Manufacturing and technologies

A typical manufacturing process of CLT includes the following steps

1) Timber selection: The primary lumber selection criteria includes, moisture content check and visual grading. The result obtained would be used to categorise timber as either construction grade CLT or appearance grade CLT and those that don't fit could be considered for different products such as plywood or glue laminated timber.
2) Drying: Selected lumbers of between 12 and 45 mm thickness are stacked in layers and then kiln-dried and conditioned down to a moisture content (MC) of 12% +/- 2% depending on the end use.

3) Lumber Planing: Lumber planing helps to activate or refreshes the wood surface in order to increase the effectiveness of gluing which ensures better bonding. Planing on all sides of the lumber should be ensured in order to attain uniform stability.
4) Finger jointing: This helps to optimize the usage of wood by making use of low grade lumbers or off cut lumbers. It also gives additional strength to the wood more than what will be provided by long stretch wood. It involves creating a finger joint on both edges of the lumber and then bonding together with adhesives.
5) Cutting lumbers to length: According to the demands of users, lumbers are reduced to size by a cutting machine and then stacked.
6) Adhesive application: The adhesive systems which are allowed for use in CLT production are Phenolic and Amino Plastic Adhesives (PRF- Phenol resorcinol formaldehyde), one-component polyurethane adhesives (1K-PUR) and Emulsion-polymer-isocyanate adhesive (EPI). Adhesive should be applied shortly after planing to overcome surface ageing and dimensional instability of the lumber thereby improving the bonding quality.
7) Panel assembly: Panel sizes is dependent on manufacturer and its end use. CLT panels can be produced in 3, 5, 7 board layers with lengths up to 18m long with typical widths of 0.5m, 1.2m and 3m. In UK the transportation of CLT plays an important role in CLT manufacture as the UK government restricts up to a practical length of 13.5m for lorries. Generally panels are manufactured up to 300mm in thickness. The assembly time is the time interval between spreading of the adhesives on different layers and the application of pressure to the layers of assembled lumbers. The assembly time set by the adhesive manufacturer should be adhered to in the manufacture of CLT. In some cases, ambient temperature that affects the performance of adhesives should also be taken into consideration in the application of adhesives.
8) Pressing of assembled panels: Pressing, a critical stage in CLT manufacture accounts for proper bonding of different layers of CLT and also determines the quality of CLT produced. Two main types of press used for CLT manufacture are vacuum press and hydraulic press.
9) Completion: The completed assembly is then planed and/or sanded before transfer to a machining station where a multi-axis machine cuts out openings for windows and doors in walls and as well as other parts. The product is then marked, packaged, shipped, delivered and then installed.

1.2 Air permeability properties of CLT

Air permeability has been defined as thermal performance of materials according to the standard (EVS-EN 12114 _2000). Air permeability is generally referred to as the rate at which air flows through a certain material such as CLT under a gradient pressure. In buildings, air permeability has been studied to have negative effect on certain performance characteristics such as thermal efficiency, sound transmission and fire proliferation. Hence, the air tight characteristics enveloped in a building is very crucial for energy management. More so, movement of air through a structure transports moisture and this can accumulate by air infiltration during hot, humid weather which may cause problems for the structure (Marcos Byttebier, 2018).

There were no standards for testing permeability of materials until 1986. Bomberg and Kumaran (1986) discovered it is possible to measure air permeability across a specimen by determining the air flow through the specimen at different pressure differentials. Air permeability is represented by the following equation: (Alsayegh, 2012).

$$ka = l\frac{Ja}{(A.\Delta p)} \quad (1.1)$$

Where ka is the air permeability [kg/Pa s·m], Ja the air flow rate [m3 /s], A the exposed surface area [m2], and Δp the air pressure difference across the specimen.

1.2.1 Air permeability of the CLT panels

Because of the sorptive nature of wood which is a major component of CLT, it has the capacity to exchange water vapour until it attains moisture equilibrium with the surrounding air. Thus, wood is referred to as a anisotropic material. If wood is in a state of equilibrium with the surrounding environment and the air becomes drier, the wood will lose water (or desorb) until it attains equilibrium. The term sorption is applied to the combined or general phenomena of adsorption and desorption (Robin Shmulsky *et al*., 2011). In building envelopes, CLT is often used as an air barrier layer. The formation of cracks in CLT has an impact on the quality of water vapour resistance and air permeability nature of the CLT material (Kukk *et al.*, 2017).

Kukk et al. (2017) tested the effect of production technologies which includes edge bonding, initial moisture content (MC) of CLT panels and number of CLT layers (3 and 5) on the air permeability of CLT. He measured air leakage in CLT panels after panels had been conditioned in environments with different relative humidity (RH) in gradual steps (RH 75%→ RH 43%→ RH 30%→ RH 15%). Figure

1.2 is the result of air flow rate of all the testes samples after the last conditioning which showed that the five (5) layered CLT panels (WBE5L and BE5L) were the most airtight panels. He concluded that more layers in CLT helps to avoid any overlapping of gaps between laminations which are possible sources of air leakages.

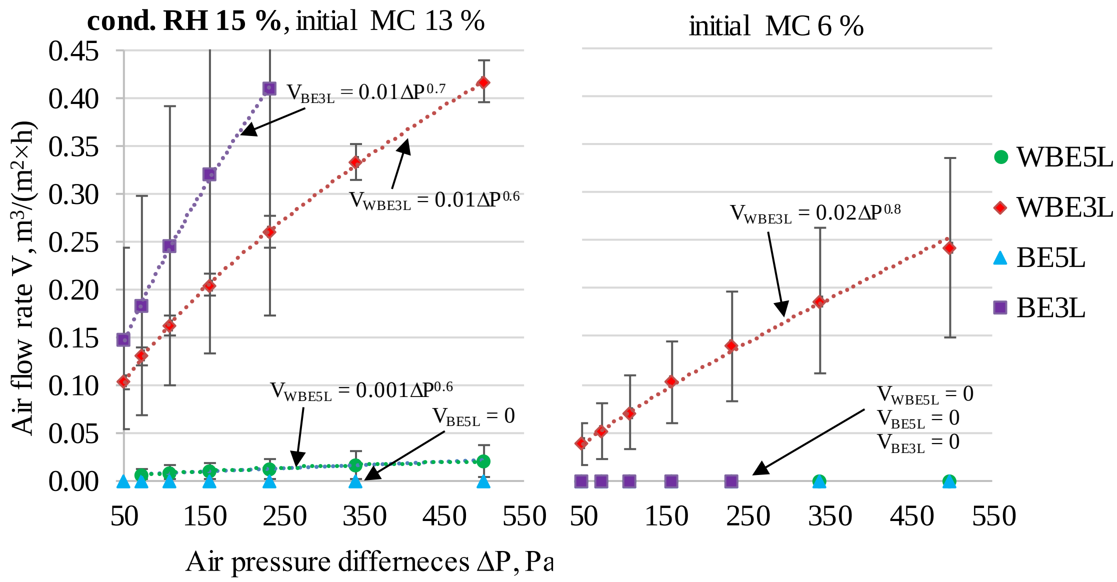

Figure 1.2: *Graph of air leakage rate of CLT panel ((Kukk et al., 2017)*

AlSayegh. (2012) carried out air permeability test on a total of nine samples all having one adhesive layer. Result showed Hem fir as the most permeable while European spruce was the least permeable to air. He compared his result to that of Wu (2007).who tested the permeability of spruce to air and he observed that the spruce made use of by Wu (2007) had higher leakage compared to European spruce. He however concluded that CLT could be impermeable and that increasing the numbers of adhesive layer could enhance its airtight property which is the same conclusion by Kukk et al.(2017).

1.2.2 Air permeability of the CLT wall connections

CLT wall connections permeability is quite different from the CLT panel permeability itself. It is becoming a general knowledge that increasing the numbers of CLT layers actually diminishes the air leakage potential via the CLT panel itself. This has made focus to shift to wall connections efficiency in CLT construction. CLT Wall connections have been found to be more susceptible to leakage characteristics than the material itself.

Skogstad et al. (2011) carried out air permeability on a variation of joints between wall to wall elements and also between wall to floor elements. Measurements were carried out on two different types of CLT (with and without Glued bonded edges) at an initial 14% MC, and after drying at 10% MC. Results showed glued board edges gave a better performance. Also, due to shrinkage and swelling at the corners of CLT boards, Air tight joints should be considered in CLT construction as this would reduce air leakage via the edges and a separate wind barrier and water vapour barrier is a better way to ensure minor air leakages through the joints of building envelopes.

Janols et al. (2013) tested the air tightness of a small test building continually over a period of six month. Construction was based on a building frame work of CLT boards. No vapour or wind barrier was present but wood fibre insulation was utilized. Between CLT panels, expandable strips was used to ensure airtightness and also for windows and doors. Results obtained after measuring recurrently over a period of six months showed a decrease in airtightness of the test building decreasing but does not affect the passive standard of the house. For proper evaluation of passive timber buildings, it was recommended to carry out airtight measurements for at least two years.

(Kalamees, Alev and Pärnalaas, 2017) studied the air leakage levels in timber frame building envelope joints. He measured eight joints with different tightening solutions for a prefabricated timber frame building envelope under laboratory conditions. Results showed largest air leakage were found at joints of external wall with external corners of wall and external wall with inserted floor, while joints with the lowest level of leakage are joints between the external wall and window. He observed that if weather barrier are well tightened, it could lead to improvement on the air tightness levels of all the joints. Using self-adhesive tape in tightening up the air-vapour barrier and the weathering barrier was found to be the most promising solution when it comes to guaranteeing the air tightness of wooden-framed structures.

1.3 Air leakages in private residences

Air leakage also called infiltration is referred to as the unintentional introduction of outside air into a building. This can be through envelopes, joints or cracks in the building or through the use of doors for passage. During different seasons of the year, the internal atmospheric condition of a building could be controlled by external atmospheric conditions through infiltration and exfiltration across pro leakage paths in the building. Movement across this leakage paths could lead to condensation in the structure resulting in mold or rot (BEC, 2011).

If a building is properly insulated, there will be less energy required to make the room comfortable for the occupant than when compared to an uninsulated room. In most cases, the general information been provided to house owners by builders is that the higher the thermal resistance (R-values) of ceiling and wall insulation, the greater the energy savings. What they are not being told is that the air leakage of a home is also a major factor in how much energy a building uses for heating and cooling. Air will leak through a building envelope that is not well sealed for as long as there is imbalance between exterior and interior atmospheric conditions which is always the case. This leakage of air decreases the comfort of a residence by allowing cold drafts, moisture, and unwanted noise to enter and may reduce the quality of indoor by allowing in dust and airborne pollutants. For effective energy-efficient building, the builder or owner of the building must ensure that all gaps that are possible source of air leakage should be sealed. For a start, it is good to ensure that windows and doors are tightly installed, but it is also important to seal joints and openings in the walls, ceiling, and flooring/foundation. The best sealing material and technology depends on the structure and building materials. To properly address the negative effects of air leakage, such as wasted energy, occupant discomfort, condensation, and so on, all of the joints and openings in the building enclosure should be air-sealed. (Stovall, Vanderlan and Atchley, 2013).

1.3.1 Minimum requirements for energy performance

The regulation of the minimum requirement for energy performance which was enacted in accordance with the building act of the Republic of Estonia (2018) was passed on the 30th of August 2012 but became effective on the 8th of January 2015. "This regulation establishes the minimum requirements for the energy performance of buildings including low energy buildings and nearly zero-energy buildings, residential buildings, new and existing buildings with indoor climate control that undergo major renovation".

In the Estonian Minimum requirements for energy performance indicator, (2018) the requirements for the building envelope includes;

1. The building envelope must be permanently airtight and sufficiently insulated.
2. In order to maintain a comfortable indoor temperature in the building, the thermal transmittance of its envelope in general may not exceed 0.5 watts per metres squared kelvin [W/ (m2K)].
3. Thermal transmittance of exterior walls should be 0.12–0.22 W/ (m2K).
4. In general, the average leakage rate of the building envelope may not exceed one cubic metre per hour and per square metre of the building envelope [m3 / (h m2)].

5. The average leakage rate of the building envelope may not exceed the value used in the energy calculation performed to prove the building's compliance with the minimum requirements for energy performance.

1.3.2 Air permeability measurements in the private residences in Estonia

Hallik and Kalamees, (2019) carried out a research on the development of airtightness of Estonian wooden buildings. The airtightness in Estonian detached and apartment buildings conducted around 2003 – 2017 were measured and the data's were obtained for further analysis. A total of 313 wooden buildings in total was considered for the research and average air leakage rates at 50 Pa for all test buildings was analysed. Result obtained after test were carried showed that median air leakage (q_{50}) of newer buildings after the updated requirements for minimum energy efficiency was 1.1m^3/ (hm^2). It was also observed that the most notable factor affecting the air tightness of buildings were quality of workmanship and supervision. In older buildings, the number of storeys had an effect on the air tightness quality but for newer buildings, this is not the case as a systematic approach has been designed that helps to ensure air tight envelope thereby avoiding large air leakages related to external walls and intermediate ceiling junctions in older buildings.

1.4 The objectives of the thesis

This research is focused on the problem of air tightness quality that is associated with the use of CLT as a construction material. Excess moisture in CLT or in wood could occur as a result of direct contact of water or water vapour with wood. Because of the anisotropic nature of wood, this generally leads to swelling and shrinkage of the wooden material in order to attain equilibrium moisture content (EMC). In the process of trying to attain EMC over a period of time, there is a reduction in volume and mass leading to formation of cracks and gaps which may ultimately result in air leakages through wall assemblies. The problem of air leakages include enhancement of fire proliferation, indoor climate in balance which means more cost on energy production, increased sound transfer which subsequently leads to decrease in quality of the structure.

The objective of this thesis was to determine the effect of moisture dry-out from CLT panels, different insulation solutions and the indoor atmospheric conditions to the air permeability properties of CLT external walls. The hypotheses of this research were formulated based on the following;

1) A more air tight insulation will make the CLT wall assembly more airtight as a result of less cracks and gaps formation compared to less airtight insulation.
2) CLT panels with higher moisture content are expected to have more air leakage due to bigger mass loss after moisture dry out compared to CLT panels with lower moisture content.

2 METHODS

This chapter describes how the air permeability test will be carried out on different test wall assemblies and the necessary criteria's that should be fulfilled in order to ensure that the procedures reflects the requirements of the EVN 12114 standard.

2.1 Test specimens

The test specimens in this research consist of 12 CLT panels in total. The specimens (Figure 2.1) are arranged into three different test walls which would be further described in details in the next sub chapter. The specimens are 5 layer CLT panels made from spruce (*Picea abies*) boards (19 x 120mm) and have bonded connections with 1K PUR (one-component polyurethane adhesives) adhesives. All 12 CLT panels were supplied directly from the manufacturer with the dimension 850x850x100 mm.

Figure 2.1: *CLT specimen used for the research*

2.1.1 Types of test walls

All the 12 specimens are placed in three different wall types (EW-1-3) which gives four CLT panels to one test wall type. For every test wall type, two are located on the southern section and two on the northern section. All 12 specimens also possess two different M.C values of 12-14% and 25-

27%. For every two sample with different MC in CLT panels and 2 located on 2 different sides of test facility directions on the northern and southern side (appendix 1).

The test walls were marked with the following abbreviations: **EW-1.1/2_N/S,** where, **EW**- external wall, **1.1/2**- first number (**1**) shows the type of the wall in which there are three different types, second (**.1/2**) shows the MC of the CLT panel. CLT panels with MC of 12-14% are identified as **.1** and with MC of 25-27% identified as **.2**, **N/S**-the location of test wall in test facility where N represents the North side and S the south side

Below (Figure 2.2-2.4) are shown the three different wall types depicting the different material layers in sections of the wall.

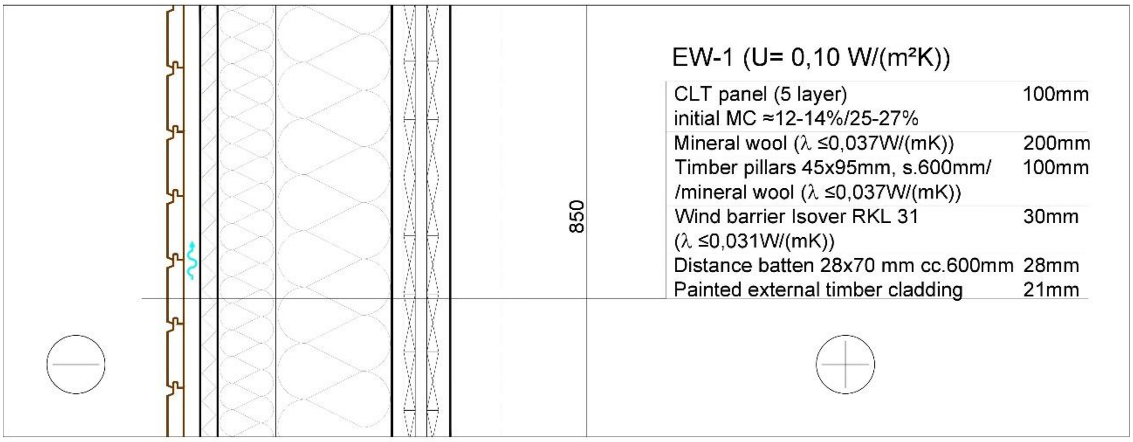

Figure 2.2: *Section of the wall type EW-1 where CLT panel is exposed to internal room and mineral wool as the insulation material (Technical drawing by Villu Kukk adjusted by the author).*

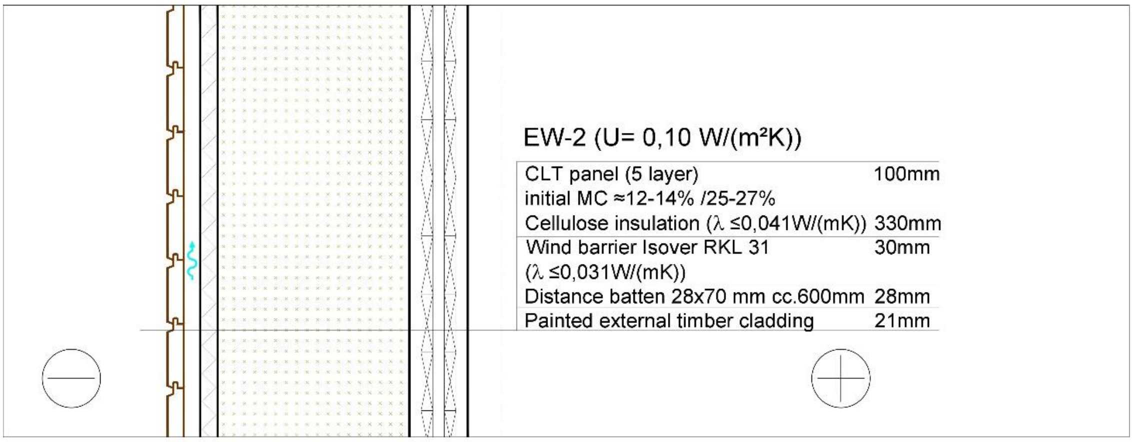

Figure 2.3: *Section of the wall type EW-2 where CLT panel is exposed to internal room temperature and cellulose as the insulation material (Technical drawing by Villu Kukk adjusted by the author).*

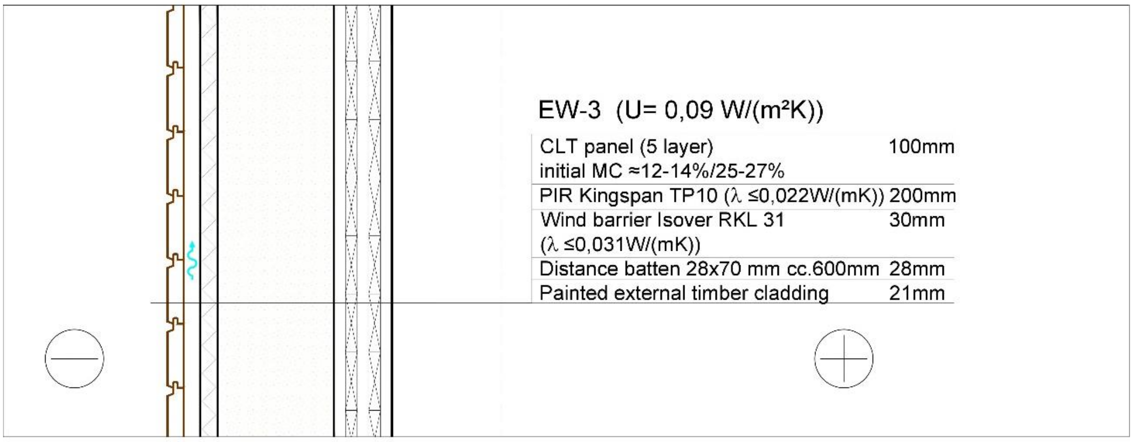

Figure 2.4: *Section of the wall type EW-3 where CLT panel is exposed to internal room temperature and PIR kingspan as insulation material (Technical drawing by Villu Kukk adjusted by the author).*

Three test wall types, exposed to the internal atmospheric condition as shown in figure 2.2 to 2.4 above, have layers of 100mm five layer CLT panel specimen, 30mm wind barrier Isover, 28mm wood batten and 21mm painted external cladding. Test walls are different from one another with the type of insulating material used and they are mineral wool insulation with thickness of 200 mm, polyisocyanurate insulation (PIR) with thickness of 200 mm and cellulose insulation with thickness of 330 mm. The three types of insulating material have different properties such as the thermal conductance with PIR having the best performance (i.e the lower the thermal conductance, the better the performance of the material) with a thermal conductance value of 0.022W/mK used in test wall type EW-3 (Figure 2.4) followed by mineral wool with a thermal conductance value of 0.037W/mK used in test wall type EW-1 (Figure 2.2) and cellulose having the least thermal insulation performance with a thermal conductance value of 0.041W/mK used in test wall type EW-2 (Figure 2.3.). All test walls can be seen to have the same thermal transmittance (U=0.1 W/m2K) (Figure 2.2 – 2.4), which means the thickness of the insulator which determines its thermal conductivity properties also have an effect on the thermal transmittance properties of the test wall.

A total of six CLT panels are wetted in order to raise the initial M.C from 12-14% to 25-27% as shown in table 2.1, while the remaining six panels were left at the M.C of 12-14% as shown in table 2.1, which was the M.C directly from the manufacturer. Raising the M.C of some of the specimens was done in order to achieve one of the objective of the research.

Table 2.1: *Table showing test specimens before and after wetting*

Test wall Identification	**MC before wetting (%)**	**MC after wetting (%)**
EW_1.1_N	14.18	27.04
EW_1.1_S	13.72	26.12
EW_1.2_N	13.57	
EW_1.2_S	13.23	
EW_2.1_N	13.51	25.43
EW_2.1_S	14.83	26.48
EW_2.2_N	14.66	
EW_2.2_S	12.73	
EW_3.1_N	14.76	25.31
EW_3.1_S	14.31	25.82
EW_3.2_N	14.46	
EW_3.2_S	13.37	

The method and procedures for wetting the panels and raising the M.C from 12%-14% to 25%-27% are discussed in details below.

Building a pool: A pool with dimensions of 5.3m by 1.8m was built with the aid of plywood, electric battery powered drill and nails. The pool was built for the purpose of keeping the CLT panels and then serving as a water containment for proper and effective wetting of the panels.

Calculating the quantity of water needed to raise the moisture content above 25%: With the aid of an electronic moisture content measurer and a weighing scale, the available existing M.C in each CLT panel was measured and the quantity of water needed for wetting to raise the M.C to the required level was calculated.

Transferring to the pool: Having completed the building of the pool and the amount of water required for wetting, CLT test panels were transferred to the pools for wetting. After transferring, the panels were wetted with the quantity of water that had been calculated beforehand and then finally covered with a nylon in order to ensure the M.C intake is equally distributed between all the CLT panels placed into the pools. For consecutive period of time, the panels were checked and MC measured in order to confirm if the panels had gotten to the required M.C.

Figure 2.5: Arrangement of CLT panels inside the pool

Impregnating the sides of the panels: After the specified CLT panels had been confirmed to attain at least 25% moisture content, they were stacked in an atmosphere of about 95% of relative humidity to attain equilibrium moisture content. The sides of the panels were later impregnated with a moisture resistance paint. This helps to ensure that moisture is not lost along the end sections of the panels. After impregnation**,** we now had in total 12 side painted CLT bonded lamination panels.

2.1.2 Structure and location of the test walls

As stated earlier, the test specimens in this research are considered as the test walls which are 12 in total. The 12 test walls are located in TTU nZEB (nearly zero energy buildings) technological test facility as a part of an external wall (EW) in the north (N) and south (S) side as shown in appendix 1. For reference purpose, it is to be noted that 24 test walls are available in the test location, my research covered only 12 test walls. Construction of one of the test wall is as shown in figure 2.6 below. The figure shows a test wall with a layer of mineral wool insulation. The CLT sample is completely sealed along the corner with a sealing tape. An 18mm water proof (film faced) plywood was used to create a wall for the test sample as shown in figure 2.6

Figure 2.6: *One of the test wall used in the research with mineral wool as insulation*

Figure 2.7 below gives a section of one of the test wall type EW 1. Between the plywood and the CLT specimen itself was used a polyurethane foam. This serves the purpose of accommodating for the swelling nature of the CLT specimen during service. The polyurethane foam can be said not to be a fully air tight material, hence an air tight adhesive sealing tape was used in ensuring a fully air tight test wall as shown in figure 2.7 below.

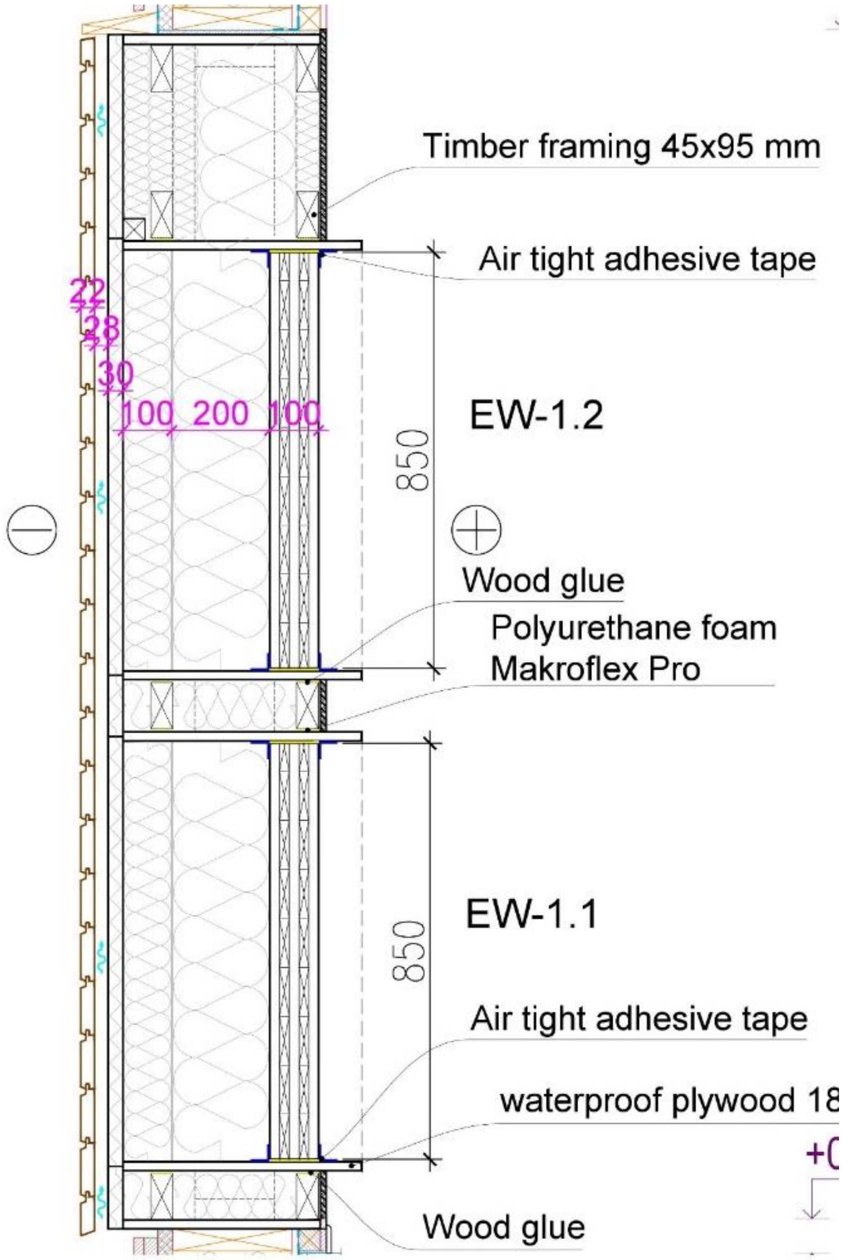

Figure 2.7: *Section of test wall depicting different materials used in ensuring proper connection of the structure (Technical drawing by Villu Kukk adjusted by the author).*

The mounting of the test walls was achieved with frames and beams already constructed as shown in fig 2.8, hence all that was needed was to transport the test walls from the TTU civil engineering laboratory to the nZEB technological test facility shown in appendix . All the 12 test walls were mounted on both North (six test walls) and South side (six test walls) as shown in fig 2.8 with the 12-14% M.C test walls arranged at the top while the 25-27% M.C arranged below. The architectural drawing in figure 2.9 gives a detailed information about the arrangement of the test walls.

Figure 2.8: *Picture showing test walls already mounted in technological test facility*

2.2 Air permeability test

The air permeability properties through the test specimens were measured according to EVS- EN 12414: 2000 “Thermal performance of buildings. Air permeability of building components and building elements. Laboratory test methods”. The measurements were performed in TTU nZEB (nearly zero energy buildings) technological test facility.

2.2.1 Apparatus for air permeability test

The test apparatus shall include the following (see Figure .2.9 and 2.10).

1. Airtight test rig- made with flat stainless steel and plywood board which were used to cover the test wall where test specimen (CLT panel) was fitted.
2. Air hoses between different equipment to apply a controlled air pressure difference over the test specimens.

3. Manometer for measuring the applied air pressure difference (Huba control 699 with pressure range of 0 – 1,600 Pa and tolerance 0.7%).
4. Air flow meter with integrated flow adjustment valve for measuring the air flow rate which is the volume of air transferred to or from a system divided by time with unit of litres/minutes (SMC_PFM 710, flow rate range 0.2 – 10 l/min, minimum unit setting 0.01 l/min, repeatability ± 1%).
5. Air compressor.
6. Air filter with air pressure difference regulator.
7. Adhesive sealing tapes for sealing all possible leakage points in the test wall.

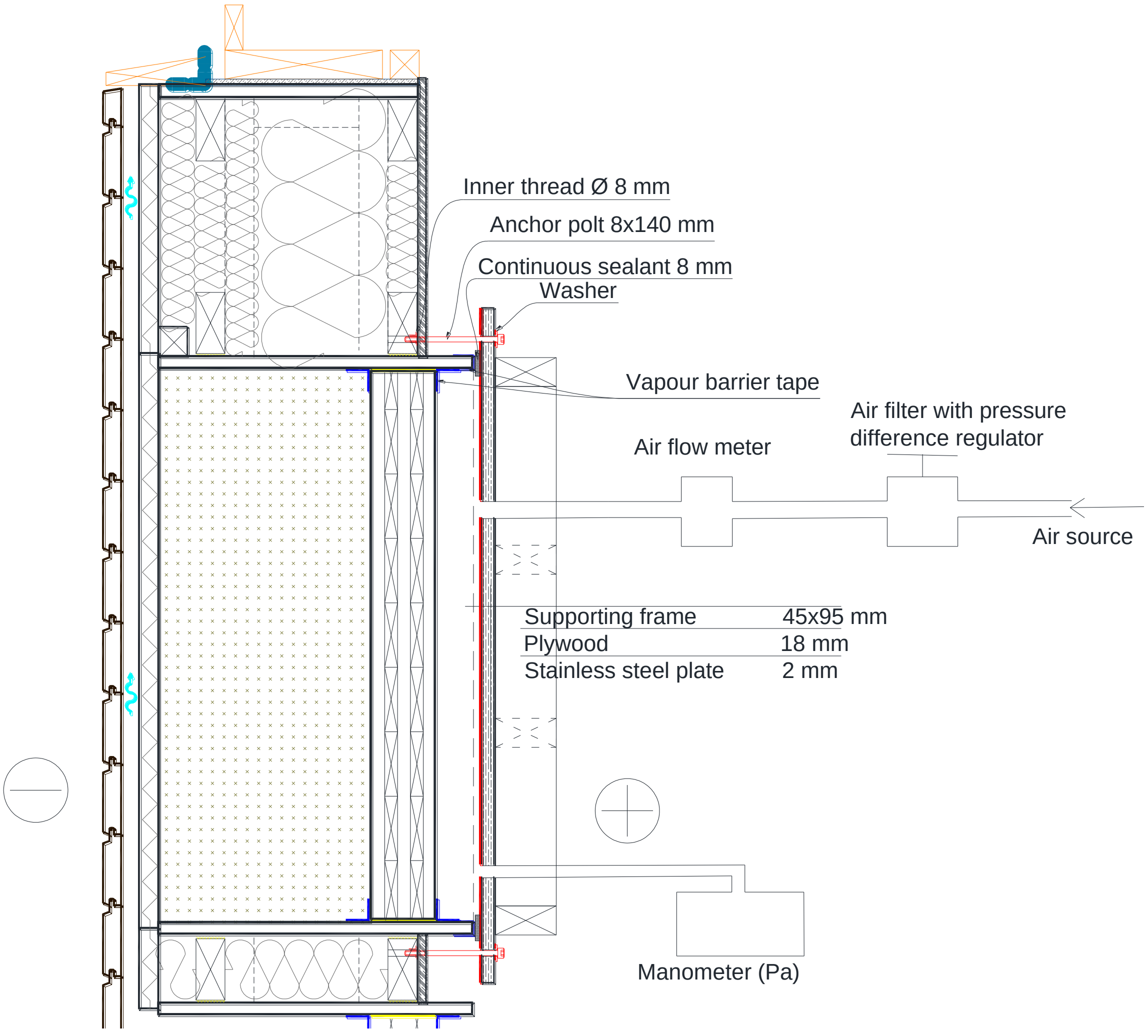

Figure 2.9: *A sectional scheme of the apparatus to be used for the air permeability test (Technical drawing by Villu Kukk adjusted by the author).*

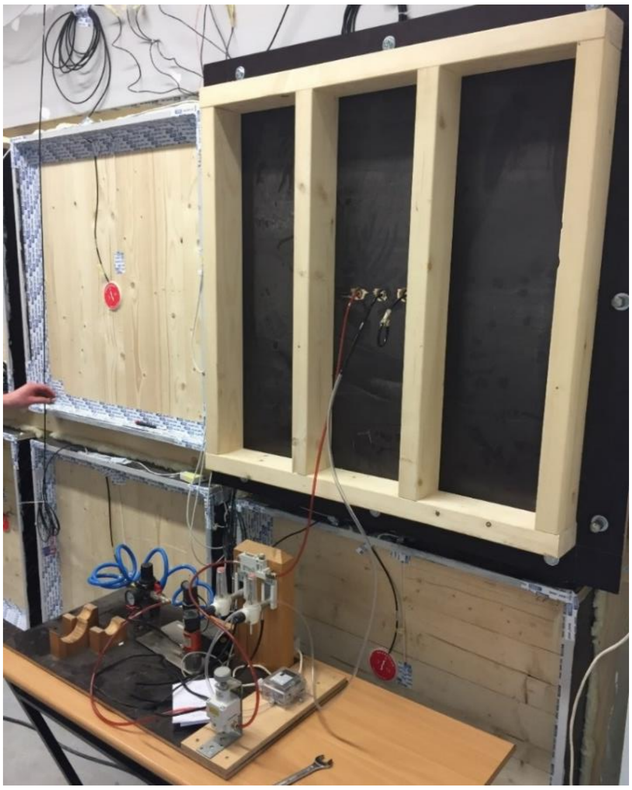

Figure 2.10: *A scheme of the apparatus to be used for the air permeability test*

2.2.2 Test procedure

For this research, test was carried out at the TTU nZEB technological test facility (Figure 2.8 and 2.9) at positive pressure differences with the apparatus provided for in Figure 2.10 and 2.11. The ambient temperature and humidity in the apparatus is between 15 ^{o}C to 30 ^{o}C and 25% to 75% RH as specified in EVS-EN 12114: 2000.

Pressure was applied to specimens in two stages according to EN 12114:

1) I stage- application of three pulse pressure of 550 Pa (first measurement) and 110 Pa (second measurement) which is equivalent to a pressure difference of 10% greater than the maximum pressure difference of 500 Pa and 100 Pa was applied to the specimens in which every pressure pulse was held for at least three seconds. At each pulse of 550 Pa in first measurement and 110 Pa in second measurement, air flow rate and static pressure difference was measured as shown in table 2.2.

2) II stage- seven steps of pressure differences (table 2.2) (between and including maximum and minimum pressure differences) were applied to the specimens in logarithmically growing pressure difference steps. Table 2.2 shows pressure differences for each pressure step. Each pressure step maintained about three seconds before results were recorded.

Table 2.2 *Pressure pulse values in Pa for each pressure pulse in stage one of pressure application*

Number of pressure pulse	**First Pressure pulse values, Δp_i (Pa)**	**Maximum pressure difference, Δp_{max} (Pa)**	**Minimum pressure difference, Δp_{min} (Pa)**	**Second Pressure pulse values, Δp_i(Pa)**	**Maximum pressure difference, Δp_{max} (Pa)**	**Minimum pressure difference, Δp_{min} (Pa)**
1	550	500	50	110	100	25
2	550	500	50	110	100	25
3	550	500	50	110	100	25

Table 2.3: *Pressure difference values in Pa for each pressure step in stage two of pressure application*

Number of pressure steps, i	**1st Pressure steps values, Δp_i (Pa)**	**Maximum pressure difference, Δp_{max} (Pa)**	**Minimum pressure difference, Δp_{min} (Pa)**	**2nd Pressure steps values, Δp_i (Pa)**	**Maximum pressure difference, Δp_{max} (Pa)**	**Minimum pressure difference, Δp_{min} (Pa)**
0	50	500	50	25	100	10
1	73	500	50	31	100	10
2	108	500	50	40	100	10
3	158	500	50	50	100	10
4	232	500	50	63	100	10
5	341	500	50	79	100	10
6	500	500	50	100	100	10

Values for each pressure step pressure difference in second stage of pressure application were calculated by following equation 1 below

$$\Delta Pi = \{10^{i(\log \Delta P\, max - \log \Delta P\, \min)}/N\} + \log \Delta P\, min \qquad (2.1)$$

Where;

N- total number of pressure steps,

i- number of pressure step.

Air flow meter used for the research could only measure up to 10 (l/min) which is equivalent to 0.88 m^3/ (m^2*h) in accordance with the area of the specimens (0.83m by 0.83m). First air permeability test was carried out about 10 months and 13 months after installation of the test walls as shown in figure 2.12 (Northern side) and 2.13 (Southern side). In figure 2.12 which is the Northern direction, the atmospheric conditions under which the first air permeability test was carried out in the space of three months conditioning between August 2018 to November 2018 was averagely at 56% RH and 20^{o}C temperature. Due to some technical challenges which was encountered and successfully tackled during the testing process, second air permeability test was carried out around March 2019 which was four months after the first air permeability test and by then, atmospheric conditions in which the specimen was placed had changed as seen in Figure 2.12 to 29% RH averagely and 21^{o}C temperature.
In figure 2.13 which shows the atmospheric conditions for the Southern side when both first and second air permeability test was carried out. First air permeability test measurement was carried out February 2019 with average atmospheric conditions of 20% RH and 21^{o}C over a period of three months (November 2018 to February 2019), while second air permeability test was carried out March 2019 with average atmospheric conditions of 36% RH and 19^{o}C temperature. One very important factor to note is the variations in the atmospheric conditions under which each test was carried out as this was a very important factor for analysing the results obtained.

The first and second air permeability test as mentioned consistently are first and second pressure steps values as shown in Table 2.1 and 2.2 .
According to the time differences for which test are carried on each test wall, we have the following abbreviations:

The test walls were marked with the following abbreviations: **EW-1.1/2_N/S,** where, **EW**- external wall, **1.1/2**- first number (**1**) shows the type of the wall in which there are three different types, second (**.1/2**) shows the MC of the CLT panel. CLT panels with MC of 12-14% are identified as **.1** and with MC of 25-27% identified as **.2**, **N/S**-the location of test wall in test facility where N represents the North side and S the south side, **1M/2M** – First measurement with pressure steps of 50, 73, 108, 158…Pa and second measurement with pressure steps of 25, 31, 40, 50…Pa.

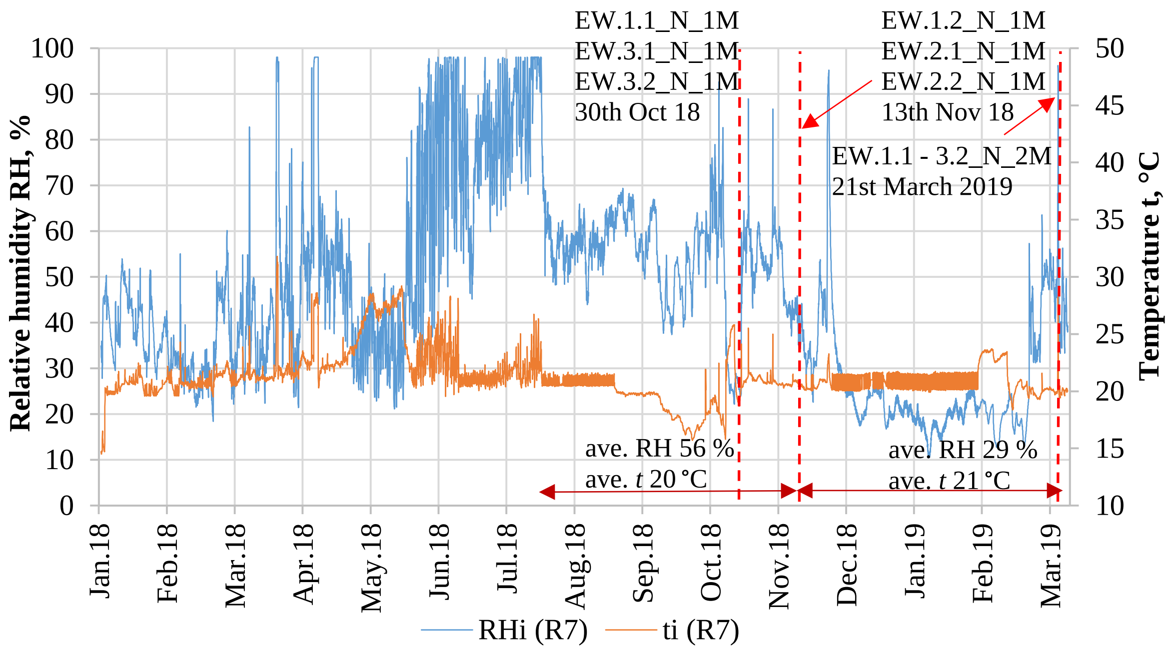

Figure 2.11: *Indoor atmospheric condition for Northern test walls location*

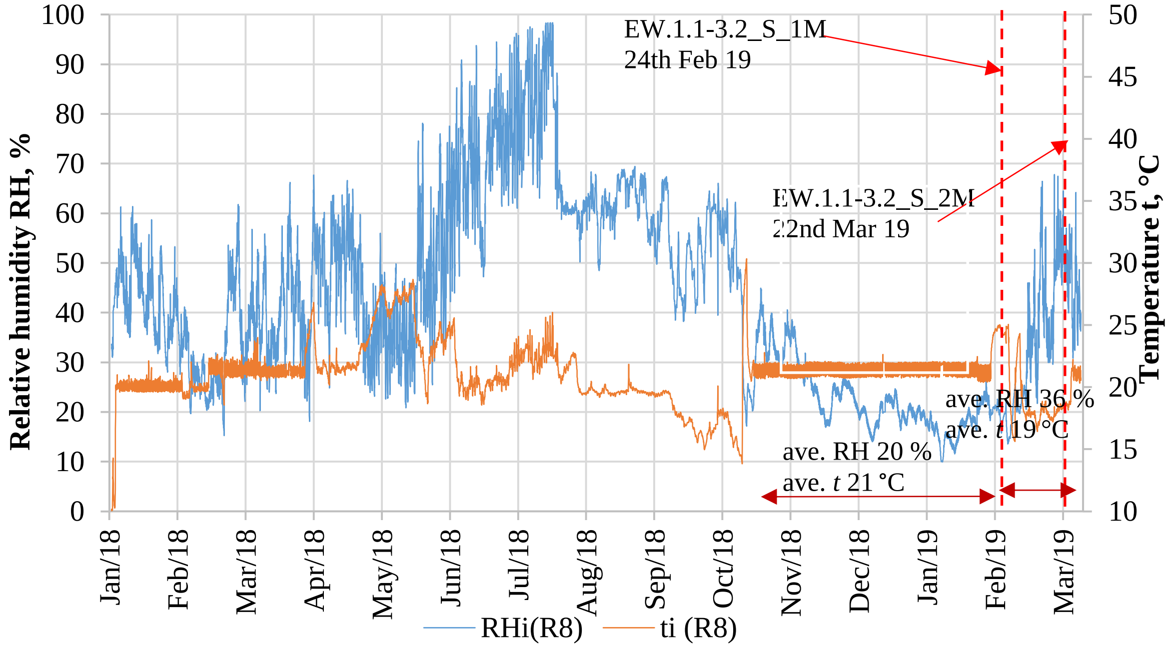

Figure 2.12: *Indoor atmospheric condition for Southern test walls location*

3 RESULTS

Air leakage measurement through all the test wall types (EW_1 – EW_3) from both the North and South directions was done. Two different set of results for air leakage measurement (first and second air permeability test results) would be discussed in this chapter. Due to technical reasons the first air permeability measurement for northern and southern walls were done in different times and therefore the previous indoor conditions before both measurements were carried out was different. The first and second air permeability test are first and second pressure difference application as shown in Table 2.1 and 2.2.

3.1 Results from first air permeability test measurements

The result of the measured air leakages through test wall types from both North and South directions are given in Table 3.1, Figure 3.1 and Table 3.2, Figure 3.2 below. The air leakages were measured at 550 Pa pulse pressure for the first stage pressure measurement and at 50, 73, 108, 158, 232, 341 and 500 Pa pressure difference for the second stage measurement over the test specimens. The air leakage was measured according to the procedures set by EVS-EN 12114: 2000.

Results of the first stage of pulse pressure application (three pressure pulse application of 550 Pa) on the test wall specimen from the Northern side as shown in Table 3.1 showed that there is air leakage through all the test specimens. The test was carried out on 30th October and 13th November 2018 as shown in Figure 2.12 which was 9 to 10 months after installation. Test walls were installed at the test location facility by January 2018 as shown in Figure 2.12 and 2.13. In Figure 2.12 which is the Northern direction, the atmospheric conditions under which the first test was carried out within the space of three months conditioning between August 2018 to November 2018 was averagely at 56% RH and 20^{o}C temperature. Values of atmospheric condition were measured by placing sensors in the rooms (test room 7 and 8 in Figure 2.9).which helps in gathering existing atmospheric condition on a daily basis. For temperature, a t-sensor referred to as omnisense A-1 with accuracy of ±0.3ºC from 0º to 60ºC range and for RH, an RH-sensor with accuracy of ±2.0ºC from 0% to 100% range.

Results from the test showed test walls EW 1.1_N, 2.1_N, 2.2_N and 3.1_N, having air flow rate at 550 Pa pressure difference greater than 10 lit/minute which is the maximum value for the air flow measuring instrument, hence maximum value of 0.88 $m^3/(m^2*h)$ derived from the area of the specimen was recorded as the results (Table 3.1). Test walls EW 1.2_N and 3.2_N had average air flow rate of 0.28 m^3/ (m^2*h) and 0.51 m^3/ (m^2*h) with test wall EW 1.2_N observed and seen to being the most air tight.

Accordingly, the test for the Southern side was carried on the 24th of February which is three months after the first measurement of the Northern side walls. Existing atmospheric conditions over a three months previous span (November 2018 – February 2019) for which the Southern test was done is observed to be at an average RH of 20% and average temperature of 21 °C.

The results of Southern side test walls, as seen in Table 3.2, showed air leakages with values greater than 10 l/minute at 550 Pa pressure for all test walls unlike results obtained in the Northern side walls where at least two test walls had least air flow rate values at 550 Pa. The differences in the results of first measurement between the Northern and Southern walls is because of the differences in the previous existing indoor atmospheric conditions under which measurements were carried out. This means that due to the hygroscopic nature of wood which allows it to adjust (either shrinking or swelling) to changes in existing atmospheric conditions in order to attain equilibrium moisture content (EMC), the CLT panel in the test wall performed differently due to this changes, hence giving rise to the inconsistencies in the result obtained after the test was carried out

The result in second pressure stage of test walls in the Northern side are shown in Figure 3.1 and Table 3.1, which was measured in logarithmically growing pressure difference steps. Smallest air leakages were observed in test walls EW 1.2_N, 2.2_N and 3.2_N and for these walls, lowest growth rate was found to be test wall EW 1.2_N with air leakage values from 0.07 m^3/ (m^2*h) to 0.14 m^3/ (m^2*h) at pressure difference 50 Pa to 158 Pa as shown in Table 3.1. The same trend was observed in the Southern side test walls where the result showed smallest air leakages in the test walls EW 1.2_S, 2.2_S and 3.2_S. The smallest growth rate to be test wall EW 1.2_S with air flow rate values ranging from 0.26 m^3/ (m^2*h) to 0.39 m^3/ (m^2*h) at pressure difference of 50 Pa to 108 Pa (Table 3.2).

The biggest air leakages in Northern side walls in second stage was observed in test walls 1.1, 2.1, and 3.1.with values already greater than 0.88 m^3/ (m^2*h) at 50 Pa which is the maximum limit of the air flow measuring instrument. The growth rate for these test walls could not be established because the measured air leakage values already exceeded the maximum limit values of equipment at 50 Pa of pressure difference (Table 3.1), hence highest observed growth rate was found in test wall 2.2 with air leakage values ranging from 0.18 m^3/ (m^2*h) to 0.46 m^3/ (m^2*h) at pressure difference 50 Pa to 158 Pa (Table 3.1). The same trend of results were also observed in the Southern walls whereby test walls 1.1, 2.1 and 3.1 all had values already greater than 0.88 m^3/ (m^2*h) at 50 Pa. The growth rate for test walls 1.1, 2.1 and 3.1 could also not be established as measured values already exceeded the maximum limit values of equipment at 50 Pa of pressure difference (Table 3.2), hence highest growth rate measured was found in test wall 3.2 with air leakage values from 0.45 to 0.72 m^3/ (m^2*h) pressure difference of 50 to 108 Pa unlike the Northern walls that has the highest growth rate of air leakages in test wall 2.2. This observation could be as a result of error due to construction of the test walls.

The result discussed above for the first air permeability test shows a clear difference in the test walls with different MC values in CLT panels. Test walls with CLT panels having MC values between 12-14% showed smaller air leakage values when compared to test walls with CLT panels having MC values between 25-27%.

Figure 3.1 and 3.2 also shows the actual air leakage values at 50 Pa which is a parameter that is used to determine the building leakage rate (EN 13829). For Northern walls and at 50 Pa, test wall 1.2 had the least air leakage value of 0.07 m^3/ (m^2*h) followed by test wall 3.2 with air leakage value of 0.11 m^3/ (m^2*h) and test wall 2.2 with most air leakage value of 0.18 m^3/ (m^2*h) For Southern walls, test wall 1.2, 2.2 and 3.2 had air leakage values of 0.26, 0.33 and 0.45 m^3/ (m^2*h) with test wall 1.2 having the least air leakage value and 3.2 having the most air leakage value.

In Figures 3.1 and 3.2, we can observe variations in different values for the flow exponent (n in V=C Δp^n). Northern test walls shows flow exponent ranging from 0.6106, 0.8292 and 0.6345 for test wall 1.2, 2.2 and 3.3 accordingly while Southern walls showed values ranging from 0.5687, 0.5264 and 0.5945 for test walls 1.2, 2.2 and 3.2. Flow exponent should range from 0.5 to 1 (Kalamees and Alev, 2017), which can be observed in all the result obtained for the first air permeability test.

Table 3.1: *Air flow rate values in first and second test stages for the first air permeability test in the northern wall*

Pressure stage	**Test pressure difference, (Pa)**	**Air flow rate (V), (m3/(m2*h)**					
		EW 1.1N	**EW 1.2N**	**EW 2.1N**	**EW 2.2N**	**EW 3.1N**	**EW 3.2N**
I	550	>0.88	0.27	>0.88	>0.88	>0.88	0.52
	550	>0.88	0.28	>0.88	>0.88	>0.88	0.51
	550	>0.88	0.28	>0.88	>0.88	>0.88	0.51
I (Avg)	**550**	>0.88	0.28	>0.88	>0.88	>0.88	0.51
II	50	>0.88	0.07	>0.88	0.18	>0.88	0.11
	73	>0.88	0.09	>0.88	0.25	>0.88	0.15
	108	>0.88	0.12	>0.88	0.34	>0.88	0.20
	158	>0.88	0.14	>0.88	0.46	>0.88	0.26
	232	>0.88	0.17	>0.88	>0.88	>0.88	0.32
	341	>0.88	0.22	>0.88	>0.88	>0.88	0.40
	500	>0.88	0.27	>0.88	>0.88	>0.88	0.49

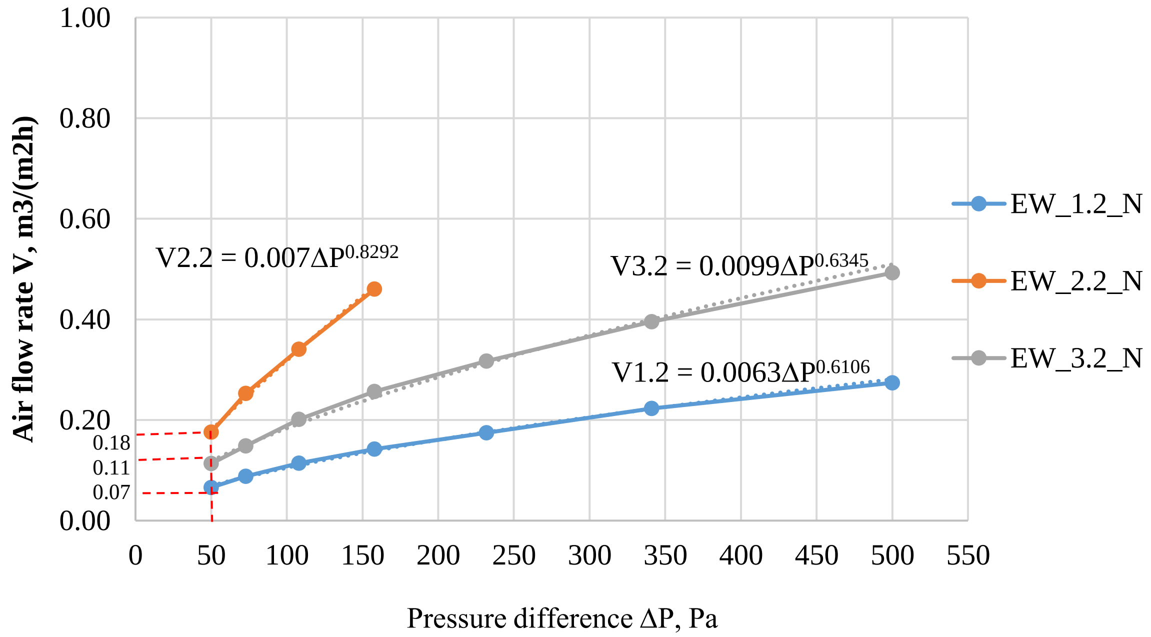

Figure 3.1: *Growth rates of air flows of test specimens in second pressure test stage for northern walls*

Table 3.2: *Air flow rate values in first and second test stages for the first air permeability test in the southern wall*

Pressure stage	Test pressure difference, (Pa)	V(m3/(m2*h))					
		EW 1.1S	EW 1.2S	EW 2.1S	EW 2.2S	EW 3.1S	EW 3.2S
I	550	>0.88	>0.88	>0.88	>0.88	>0.88	>0.88
	550	>0.88	>0.88	>0.88	>0.88	>0.88	>0.88
	550	>0.88	>0.88	>0.88	>0.88	>0.88	>0.88
I (Avg)	550	>0.88	>0.88	>0.88	>0.88	>0.88	>0.88
II	50	>0.88	0.26	>0.88	0.33	>0.88	0.45
	73	>0.88	0.32	>0.88	0.39	>0.88	0.56
	108	>0.88	0.39	>0.88	0.48	>0.88	0.72
	158	>0.88	0.48	>0.88	0.59	>0.88	>0.88
	232	>0.88	0.61	>0.88	0.73	>0.88	>0.88
	341	>0.88	0.77	>0.88	>0.88	>0.88	>0.88
	500	>0.88	>0.88	>0.88	>0.88	>0.88	>0.88

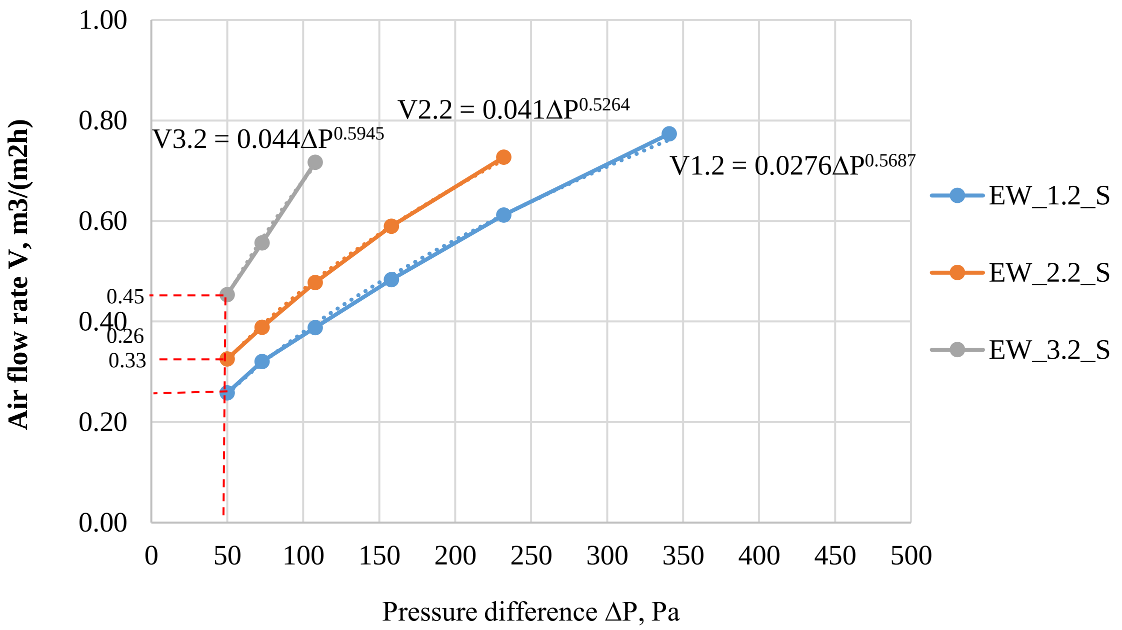

Figure 3.2: *Growth rates of air flows of test specimens in second pressure test stage for southern walls*

3.2 Second measurement results for air permeability test

The result of the measured air leakages through test wall types from both North and South sides are given in Table 3.3, Figure 3.3 and Table 3.4, Figure 3.4 below. The air leakages were measured at 110 Pa for the first stage pressure measurement and 25, 31, 40, 50, 63, 79 and 100 Pa pressure difference for the second stage measurement over the test specimens.

Results of the first stage of pulse pressure application (three pressure pulse application of 110 Pa) on the test wall specimen from the Northern side as shown in Table 3.3 showed air leakage properties through all the test specimens. The test was carried out by 21st March 2019 as shown in Figure 2.12 which was about 13 months after installation. Average RH of previous three months (December 2018 – March 2018) before commencement of second measurement was 29% and average temperature was 21 °C.

Test walls EW 1.1_N, 2.1_N, 2.2_N and 3.1_N was observed to have air flow rate greater than 10 lit/minute at 110 Pa pressure which is the maximum value for the air flow measuring instrument, hence maximum value of 0.88 m^3/ (m^2*h) derived from the area of the specimen was recorded as the results (Table 3.3). Test walls EW 1.2_N and 3.2_N had average air flow rate of 0.16 m^3/ (m^2*h) and 0.25 m^3/ (m^2*h) with test wall EW 1.2_N observed and seen to being the most air tight.

Moreso, the results of Southern side walls as seen in Table 3.4 showed air leakages through all the test specimens when the first stage pressure pulse of 110 Pa was applied. The test was carried out by 22nd March 2019 as shown in figure 2.13 which was about 13 months after installation with the average RH of the previous one month before second measurement to be 36 % and average temperature was 19 °C. Test walls EW 1.1_S, 2.1_S, and 3.1_S was observed to have air flow rate greater than 10 lit/minute at 110 Pa pressure which is the maximum value for the air flow measuring instrument, hence maximum value of 0.88 m^3/(m^2*h) derived from the area of the specimen was recorded as the results (Table 3.4). Test walls EW 1.2_S, 2.2_S and 3.2_S had average air flow rate of 0.39, 0.48 and 0.69 m^3/ (m^2*h) with test wall EW 1.2_S observed and seen to being the most air tight, unlike results obtained in the Northern side where only two test walls (EW 1.2_N and 3.2_N) had least air leakage values at 110 Pa. In all the results obtained, test wall EW 1.2 (with initial MC of 12-14 %) had the least air leakages compared with all other test walls.

The result in second pressure stage of test walls in the Northern side shown in Figure 3.3 and Table 3.3, which was measured in logarithmically growing pressure difference steps showed smallest air leakages in test walls EW1.2N, 2.2_N and 3.2_N with test wall EW 1.2_N having lowest growth rate with air leakage values from 0.06 to 0.15 m^3/ (m^2*h) at pressure difference of 25 Pa to 100 Pa. The same trend was again observed in the southern side test wall where the result showed smallest air leakages in the test walls EW 1.2_S, 2.2_S and 3.2_S. The smallest growth rate to be test wall EW 1.2_S with air flow rate values ranging from 0.16 m^3/ (m^2*h) to 0.34 m^3/ (m^2*h) at pressure difference 25 Pa to 100 Pa (Table 3.4). The trend of the result for both walls on both direction was found to be the same but a slight difference is that Northern walls seems to be more air tight than Southern walls due to smaller air leakages as can be observed in the results obtained. This could also be as a result of human error during the testing process.

Biggest air leakages in Northern walls during second stage measurement was observed in test walls 1.1, 2.1 and 3.1 with values at 25 Pa pressure difference already greater than 0.88 m^3/ (m^2*h) which is the maximum limit of the air flow measuring instrument. The growth rate for these test walls could again not be established because the measured values already exceeded the maximum limit values of equipment at 25 Pa of pressure difference. (Table 3.3), hence highest growth rate was recorded in test wall 2.2 with air leakage values from 0.40 m^3/ (m^2*h) to 0.84 m^3/ (m^2*h) at pressure difference 25 Pa to 100 Pa (Table 3.3). The same trend of results were also observed in the Southern walls whereby test walls 1.1, 2.1 and 3.1 all had values already greater than 0.88 m^3/ (m^2*h) at 25 Pa. The growth rate for test walls 1.1, 2.1 and 3.1 could also not be established as measured values already exceeded the maximum limit values of equipment at 25 Pa of pressure difference (Table 3.1), therefore highest growth rate was found in test wall 3.2 with air leakage values from 0.27 to 0.64 m^3/ (m^2*h) at pressure difference of 25 to 100 Pa.

Results for second air permeability measurement equally shows a clear difference in the test walls with different MC values in CLT panels when compared with the first air permeability measurement. This means test walls with CLT panels having MC values between 12-14% showed smaller air leakage values than CLT panels having MC values between 25-27%.

In Figure 3.3, the air leakage values at 50 Pa shows that test wall 1.2 had the least air leakage value of 0.10 m^3/ (m^2*h) followed by test wall 3.2 with air leakage value of 0.15 m^3/ (m^2*h) and test wall 2.2 with most air leakage value of 0.57 m^3/ (m^2*h). For Southern walls (Figure 3.4), test wall 1.2, 2.2 and 3.2 had air leakage values of 0.24, 0.32 and 0.40 m^3/ (m^2*h) with test wall 1.2 having the least air leakage value and 3.2 having the most air leakage value.

Finally, n values for both test walls in North and South directions as shown in Figure 3.3 and 3.4 are found to be 0.6214, 0.5398 and 0.5435 for test walls 1.2_N, 2.2_N, 3.2_N and 0.5466, 0.4824 and 0.6317 for test walls 1.2_S, 2.2_S, 3.2_S. All except for one test wall (2.2_S) of the flow exponent values are within the 0.5 to 1 range. Fluctuating pressure difference experienced during air permeability test may be a reason why the recommended range could not be achieved by this test wall.

Table 3.3: *Air flow rate values in first and second test stages for the air permeability test in the northern wall*

Pressure stage	**Test pressure difference, (Pa)**	**V(m3/(m2*h))**					
		EW 1.1N	**EW 1.2N**	**EW 2.1N**	**EW 2.2N**	**EW 3.1N**	**EW 3.2N**
I	110	>0.88	0.16	>0.88	>0.88	>0.88	0.24
	110	>0.88	0.16	>0.88	>0.88	>0.88	0.25
	110	>0.88	0.16	>0.88	>0.88	>0.88	0.25
I (Avg)	110	>0.88	0.16	>0.88	>0.88	>0.88	0.25
II	25	>0.88	0.06	>0.88	0.40	>0.88	0.11
	31	>0.88	0.08	>0.88	0.44	>0.88	0.12
	40	>0.88	0.08	>0.88	0.51	>0.88	0.13
	50	>0.88	0.10	>0.88	0.57	>0.88	0.15
	63	>0.88	0.11	>0.88	0.66	>0.88	0.17
	79	>0.88	0.13	>0.88	0.74	>0.88	0.20
	100	>0.88	0.15	>0.88	0.84	>0.88	0.23

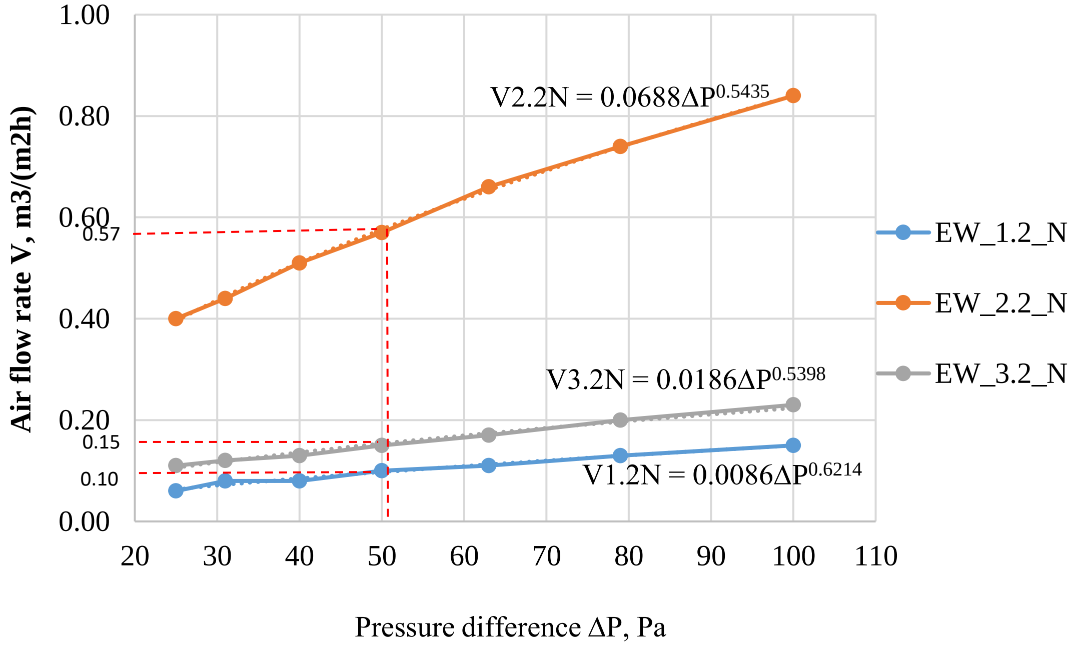

Figure 3.3: *Graph of second stage pressure growth step of all test walls on the north side*

Table 3.4: *Air flow rate values in first and second test stages for the air permeability test in the southern wall*

Pressure stage	Test pressure difference, (Pa)	V(m3/(m2*h))					
		EW 1.1S	EW 1.2S	EW 2.1S	EW 2.2S	EW 3.1S	EW 3.2S
I	110	>0.88	0.37	>0.88	0.48	>0.88	0.69
	110	>0.88	0.39	>0.88	0.48	>0.88	0.68
	110	>0.88	0.40	>0.88	0.48	>0.88	0.69
I (Avg)	110	>0.88	0.39	>0.88	0.48	>0.88	0.69
II	25	>0.88	0.16	>0.88	0.23	>0.88	0.27
	31	>0.88	0.19	>0.88	0.26	>0.88	0.30
	40	>0.88	0.22	>0.88	0.29	>0.88	0.35
	50	>0.88	0.24	>0.88	0.32	>0.88	0.40
	63	>0.88	0.28	>0.88	0.35	>0.88	0.47
	79	>0.88	0.32	>0.88	0.40	>0.88	0.55
	100	>0.88	0.34	>0.88	0.46	>0.88	0.64

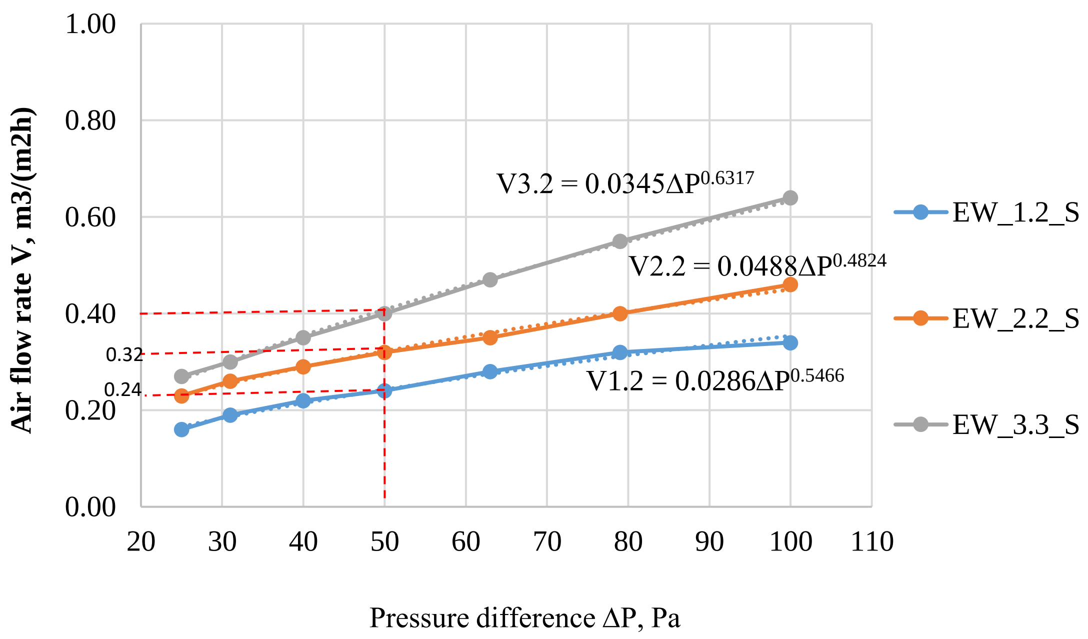

Figure 3.4: *Graph of second stage pressure growth step of all test walls on the south side*

3.3 Comparison of the result from first and second measurement

In comparing the first and second measurement, this helps to fully understand the effect of previous existing atmospheric condition and MC values on the CLT specimens in test walls. This comparison was done by making use of the air leakage values of both measurements at 50 Pa pressure difference. Figure 3.5 and 3.6 below shows the air leakage rate of all test walls (both first and second measurement) at 50 Pa (parameter used to determine the building air leakage rate (EN 13829)).

Figure 3.5 shows air leakage values at 50 Pa pressure difference of both first and second measurement from the Northern direction. In the results obtained, it was observed that test walls EW_1.1/2.1/3.1_N_1/2M (CLT panels of 25 -27% M.C) all had the highest air leakages which falls above the maximum reading value of the equipment. All other test walls in Figure 3.5 EW_1.2/2.2/3.2_N_1/2M (CLT panels of 12 – 14% M.C) also had air leakages but more air tight than the former with EW_1.2_N_1M having the least air leakage value of 0.07 m^3/ (m^2*h) at 50Pa.

Air leakage values for the first and second measurement for test walls with 12 – 14% M.C values are also seen to have a positive growth rate with test wall 1.2 having the least positive growth of the air leakage at +0.03 m^3/ (m^2*h). Test wall 2.2 was observed to have a very high positive growth rate of +0.39 m^3/ (m^2*h) when compared to other test walls and this could be as a result of manual error while recording result as other results are within similar range.

One very important observation is the positive growth rate of air leakage values between the first and second measurement which can be further explained by considering the atmospheric conditions under which each test was carried out. From figure 2.12, first measurement was done at 56% RH while second test was done at 29% RH which obviously mean both tests were carried out under different atmospheric conditions. Therefore the decrease in the RH value led to changes in EMC of CLT panel in test walls. From Table 3.5, EMC changed from approximately 10% (at 56% average RH and 21ºC average temperature) to 6.2% (at 29% average RH and 21ºC average temperature). The loss in the EMC due to changes in the atmospheric condition led to deformation of the CLT panel in test walls making them to shrink, which presumably was the reason for the bigger air leakage, making test walls less air tight when the second test was carried out.

Table 3.5: *MC of Sitka spruce in equilibrium with RH conditions and dry-bulb (air) temperatures*

Dry bulb temp. (°C)	**RH (%)**							
	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**
-1.11	4.6	6.3	7.9	9.5	11.3	13.5	16.5	21
10	4.6	6.3	7.9	9.5	11.2	13.4	16.4	20.9
21	4.5	6.2	7.7	9.2	11	13.1	16	20.5
32	4.3	5.9	7.4	8.9	10.5	12.6	15.4	19.8
43	4	5.6	7	8.4	10	12	14.7	19.1
54	3.7	5.2	6.6	7.9	9.4	11.3	14	18.2
66	3.4	4.8	6.1	7.4	8.8	10.6	13.1	17.2
77	3	4.3	5.6	6.8	8.2	9.9	12.3	16.2

Source: Dry Kiln Operatorś...1991

Figure 3.6 shows air leakage values at 50 Pa pressure difference of both first and second measurement from the Southern direction Results obtained also showed test walls EW_1.1/2.1/3.1_S_1/2M (CLT panels of 25 -27% M.C) having the highest air leakages which falls above the maximum reading value of the equipment just like the Northern walls. Other test walls EW_1.2/2.2/3.2_S_1/2M (CLT panels of 12 – 14% M.C) had air leakage properties but displayed more air tightness when compared to the former with EW_1.2_S_2M having the least air leakage value of 0.16 $m^3/(m^2*h)$ at 50Pa making it the most air tight test wall on the Southern side.

Air leakage values between the first and second measurement for test walls with 12 – 14% MC are seen to have a negative growth air leakage (decrease) meaning second test measurement showed test walls are more air tight than test walls of first measurement. Most negative growth rate was found in test walls 3.2 with a negative growth rate value of -0.05 $m^3/(m^2*h)$ while the least was test walls 2.2 with -0.01 $m^3/(m^2*h)$ as negative growth rate value. Unlike Northern walls that had a positive growth rate, Southern walls shows exactly the opposite and we can equally observe the trends in the atmospheric condition to make an explanation for this observation.

From figure 2.13, first measurement was done at 20% RH while second test was done at 36% RH which shows exactly the opposite changes of atmospheric condition when compared to the Northern walls. This is because EMC increased by approximately 2% (Table 3.5), leading to swelling of the CLT panel in test walls which was presumably observed to have led to test walls becoming more airtight while the second air permeability measurement was carried out. For North walls, test walls for first measurement were more air tight than test walls than second measurement and RH values decreased from 56% to 29%, but for South walls, test walls for first measurement were less air tight than second measurement and RH values increased from 20% to 36% accordingly.

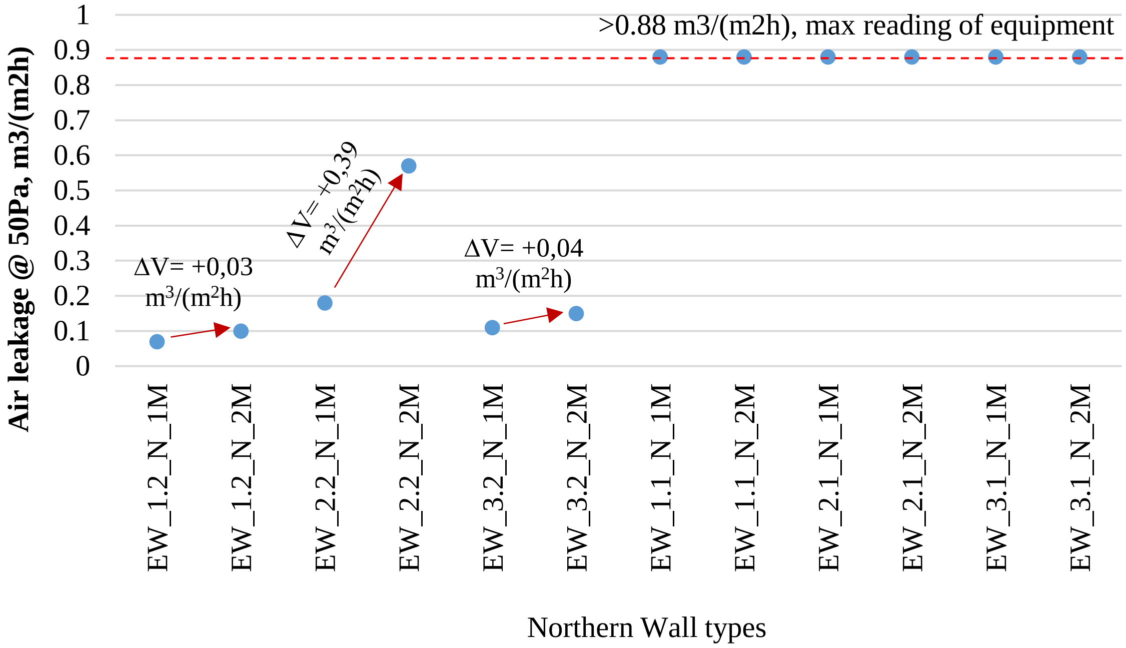

Figure 3.5: *Variations in air leakages of Northern test walls at an air pressure difference of 50 Pa*

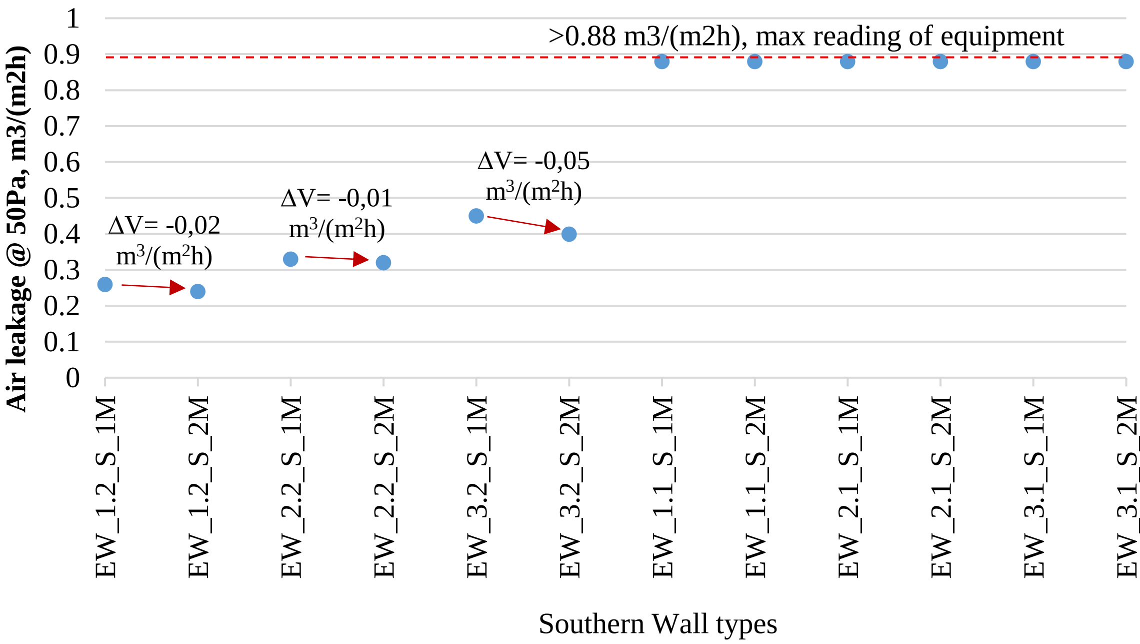

Figure 3.6: *Variations in air leakages of Southern test walls at an air pressure difference of 50 Pa*

4 DISCUSSION

The results obtained for both Northern and Southern test walls when air permeability measurements were carried out showed a trend dependent on the indoor atmospheric condition under which the test were carried out. The result for the Northern test walls between the first and second measurement showed the increase of air leakage after the second measurement. The first measurement was carried out at a RH of 56% (average RH of previous three months) and second measurement was done at 29% (average RH at three months after first measurement), which presumably led to decrease of MC in panels up to 3.8%. Conversely, the result for the Southern test walls between first and second measurement showed the decrease of air leakage where first measurement was done at RH of 24% (average RH of previous three months) and second measurement was at 36% RH (average RH of previous one month after first measurement) and the EMC increased presumably up to 2%. Wood behaves in an anisotropic manner which allows it to attain equilibrium moisture content with respect to existing atmospheric condition. This means wood would either shrink or swell in order to attain EMC depending on the changes of atmospheric condition. Decrease in EMC leads to mass loss of wood and therefore a volumetric shrinkage and vice versa. The volumetric shrinkage or swelling of each board in CLT panel leads to formation of gaps between the laminations (gaps between adjoining boards) and cracks in the middle of the laminations. Cracks and gaps in the CLT panel surface are the main source of the air leakages in the panel (Kukk et al. 2017). Based on the result of the study, it can be said there is a considerable effect of the indoor environment to the air permeability properties of CLT walls in the case where the CLT panel is exposed to the environment. As indoor relative humidity decreases, air leakage in the CLT wall increases and vice versa. Therefore during the winter in the Estonian climate, where the indoor RH reaches a minimum, the air leakages can be expected to be biggest in the CLT walls.

Secondly, the second air permeability measurement for both Northern and Southern sides carried out around the same time (21st March and 22nd March 2018) under the same atmospheric condition (29% RH and 21ºC Temperature) over a period of three previous months is worth discussing to see if other factors such as insulation properties and directions of the walls had an effect on the air permeability properties of CLT panels in test walls. There was no clear pattern in the result according to the different type of insulations in the Northern and Southern test walls after the second air permeability measurements. One of the hypothesis on which this research was formulated was that the use of air tight insulation for CLT walls would create an overall airtight wall assembly. The results of this study did not confirm the given hypothesis. The least air leakage was observed in test walls insulated with mineral wool (with initial MC of 12-14% in CLT), which is not an airtight insulation. Test walls insulated with PIR insulation (with initial MC of 12-14% in CLT), which is considered as airtight, had bigger air leakages compared to the test walls insulated with mineral and cellulose wool in the North side and bigger leakage compared with mineral wool insulation in South side test walls. With all the observation discussed above about the directions and insulation properties having an effect on the air permeability of CLT panels in test wall, it can be said that neither insulation nor directions does affect the performance of CLT panels relative to air permeability properties as results obtained does not present a definite pattern, hence not sufficient enough for concluding on such an hypothesis. The future research is recommended to confirm or refute the given hypothesis with larger scale test wall samples.

Thirdly, the air permeability results in both first and second measurement showed clear difference between test walls with different initial MC in CLT panels. Test walls with initially higher MC were observed to have the largest air leakages. At 50 Pa of pressure difference, the measured air leakages in all specimens with initial higher MC (25-27%) exceeded the maximum reading of the equipment while other test walls with initial lower MC (12-14%) had considerable lower air leakages. Previously it was concluded that the environment has an effect on the air permeability properties of CLT wall assemblies where panels are exposed to the indoor environment. Comparing the results between specimens with different initial MC it is seen much bigger effect on the air permeability properties on the CLT test walls. The second hypothesis for this research was formulated based on the premises that CLT test walls with panels having higher initial moisture content are expected to have bigger air leakage due to bigger mass loss in the panel during service, compared to CLT panels with lower moisture content. Hence, the second hypothesis for this research can be confirmed as results clearly showed that CLT panels with initial MC of 25-27% had considerably bigger air leakages when compared to CLT panels with initial MC of 12-14%. Previous studies found that initial higher MC, above 17% ((Kukk *et al.*, 2019) may lead to possible moisture damage as a mold growth which can be managed by drying out. Another threat of high initial MC is big air leakages (greater than 0.88 $m^3/(m^2*h)$ as revealed by the results of this study, which cannot be avoided by drying out as in the case of moisture damage. This is because the drying out of the moisture still leads to the mass loss of the timber which is the cause of the big air leakages as our test result showed. Thus, in designing a CLT building envelope where the CLT is to be considered as an air tight layer and would also be exposed to the indoor environment, it is recommended to avoid contact with water during the construction stage as this can increase the initial MC to a level that could lead to air leakage which may affect the energy performance of the building. The more air tight the building is, the lower the energy consumption (Saari *et al.*, 2012)

Hallik et al, (2019) measured the airtightness of Estonian detached and apartment buildings. Airtightness of a total of 313 wooden buildings between 2003 to 2017 was measured and analysed to determine the average air leakage rates at 50 Pa for all test buildings. Result obtained showed that new buildings which were constructed after the updated minimum requirements for energy efficiency had a median q50 of 1.1 m3/ (hm2) with values ranging from 0.8 to 3.1 m3/ (hm2). In this research, test walls with CLT panels (initial MC 25 – 27%) had air leakages above 0.88 m3/ (hm2) at 50 Pa pressure difference which could rise above 1.1 m3/ (hm2) as their actual values could not be determined due to the capacity of air flow measuring instrument. This further re-emphasizes the findings of this research with regards to the relationship between high initial MC of CLT and air leakage as already discussed. The dimension of the test walls for this research is 0.83m by 0.83m, if the air leakages of test walls with higher initial MC in CLT panels are higher than air leakage values of certain building envelopes as obtained by, Hallik and Kalamees (2019) then such test walls configurations should not be encouraged. Similar or better results can be achieved with test wall 1.2 where initial MC of the CLT panel used as airtight layer does not increase during construction as this may lead to bigger air leakage.

Kukk et al, (2017) measured the air leakages of CLT panels produced with the similar technology which is a 5 layered CLT panel without bonded edge, (WBE5L) conditioned in environments with different relative humidity (RH) in gradual steps of RH (RH 75%→ RH 43%→ RH 30%→ RH 15%). Figure 4.1 below shows the result obtained.

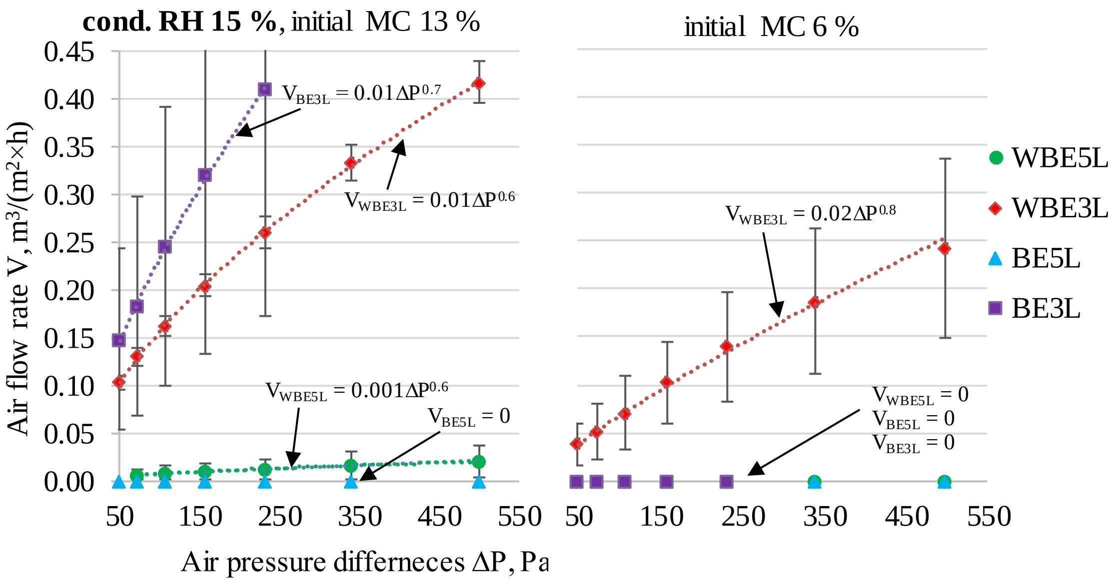

Figure 4.1: *Graph of air leakage rate of CLT panel ((Kukk et al., 2017)*

Result showed WBE5L CLT specimen with 13% initial MC, conditioned at 15% RH had air leakage value of approximately 0.025 m3/ (hm2) at 500 Pa pressure difference, which is approximately 10 times smaller when you compare with the result of test wall 1.2N_1M (most air tight test wall) obtained in this research. This could mean that the CLT specimens used in this research may not really be the likeable source of air leakage in test walls but via other leakage points. Smoke detector was utilized to determine if the source of air leakage could have come from the air tight rig itself as shown in Figure 4.2 below, but no air leakage point was detected along the air tight rig. Smoke detectors was moved all-round the four external sides of the test wall during each air permeability test measurement.

Figure 4.2: *Tracing air leakage points along test rig with smoke detector*

Another potential source of air leakage path that was also considered which seems to be the most likeable option is along the cracks and gaps of the surface of the CLT panel. These cracks and gaps allows air leakage to escape through the foams and between the foams and connecting elements on the four sides of the wall as shown in figure 4.3

Adhesive sealing tapes were used to cover the edges of the CLT panels as shown in Figure 4.3 below. The aim of using the sealing tapes is to ensure the test wall is fully airtight, but on a closer look, the sealing tapes cannot control the leakages via cracks, meaning once cracks becomes visible on the CLT panels, the tendency of test walls becoming air tight is minimized as the cracks become a pathway for air to escape. Between the plywood material acting as a wall and the CLT panel is a layer of polyurethane foam which helps to cater for the swelling and shrinkage of the CLT material itself during service. This polyurethane material itself which was used for this project is not an airtight proof material, hence if the opportunity arises for it to be a funnel for air leakage, it's going to serve that purpose effectively. So, when cracks are created on the CLT panel and the cracks are formed all through the length of the CLT, then there is the possibility that when air in form of pressure difference is applied onto the specimen, there is every tendency that air would find its way along the cracks, through the polyurethane foam as shown in Figure 4.3 thereby making the test walls not airtight and then leading to the high values of air leakage observed for this research.

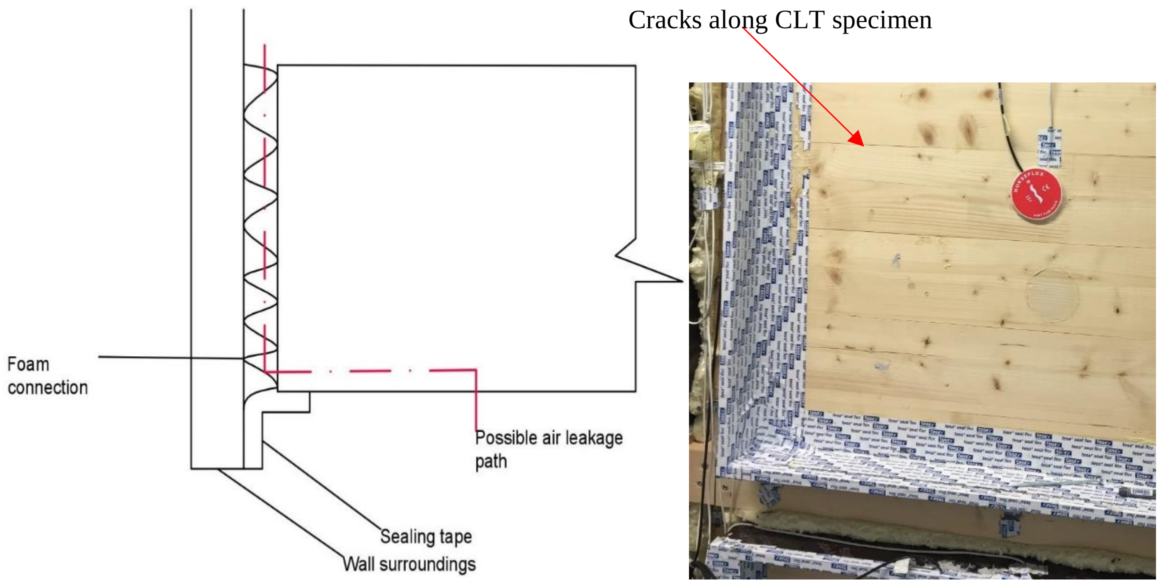

Figure 4.3: *Pathways for air leakages along cracks on the CLT specimen*

Two major problems were encountered in this research. The first one was the measuring range of the air flow meter which was from 0 to 10 lit/min. Any leakage value outside of the range became undefined measurement. An air flow meter with wider measuring range must be considered for future measurements to cover all test walls including test walls that had MC value of 25-27%. This would enable us to have more results to analyse and observe a better pattern for all the test walls in this research, but that notwithstanding, a pattern was still observed for the results obtained and justifiable conclusion were made with these results.

Secondly, the wall connections used in building the CLT test walls could have been made to be more airtight than what is currently available. As initially explained, massive air leakages were observed for most of the test walls and the leakage paths was found to be through the cracks formed along the CLT panel right through the polyurethane foam found between the plywood material and the CLT panel itself. The polyurethane foam itself is not a fully airtight material which then became the pathway in most test walls for air leakages during air permeability test. A better wall connecting system that is fully airtight would have improved the air tightness of the test walls, making it possible to obtain more results that would have still been useful in analysing the results of the research work.

For future research, it is recommended that a much bigger sample size test wall would be a better fit to really understand the effect of insulation on the air permeability properties of CLT test walls as results obtained in this research does not clearly offer a precise pattern to conclude on the performance of insulation material. The connections of building elements in CLT envelopes also requires improved future research as it was observed in this research that sealing tapes and polyurethane foam may not really be the best materials to ensure proper sealing of the element connections. Kalamees et al, (2017) found that using adhesive tapes for sealing the water vapour barrier is the most promising solution for guaranteeing air tightness of wooden framed structures, but in this research the result showed that CLT element connections requires additional sealing solution beside using only the adhesive tape.

CONCLUSIONS

This research was done in order to determine the air permeability property of CLT in different test wall assemblies. 12 test walls in total were considered and the differences of test walls were in the percentage of initial MC available in CLT panels, the insulation material present in test walls and the directions in which test walls were located. The effect of initial MC in CLT panels, existing indoor atmospheric conditions and insulation properties relative to the air leakage performance of all the test walls was determined. Two hypothetical statements were created in the beginning of this research:

1) A more air tight insulation will make the CLT wall assembly more airtight as a result of less cracks and gaps formation compared to less airtight insulation.
2 CLT panels with higher moisture content are expected to have more air leakage due to bigger mass loss after moisture dry out compared to CLT panels with lower moisture content.

Three major conclusions were deduced from this research:

1) Results obtained points to the fact that indoor environment has a considerable effect on the air leakage performance of the test walls. A decrease in indoor RH gave rise to bigger air leakage in test walls with CLT panels having initial MC (12-14%) and vice versa. For test walls with CLT panels having initial MC (25-27%), a definite pattern for the result obtained could not be obtained as test walls had air leakage values in the excess of the measuring instrument utilized for this research.

2) Secondly, initial MC available in CLT panel was also confirmed to influence the air leakage performance of test walls. Result obtained confirmed that test walls with low initial MC in CLT panels were found to be more air tight than those with high initial MC in CLT panels. Results also showed that the effect of initial MC of CLT panels also had a bigger effect on air permeability properties than indoor environment.

3) Thirdly, the effect of insulation could not be ascertained in this research as results obtained were not precise enough to make conclusion on such findings. Though, test walls with mineral wool insulation were observed to being the most air tight wall as can be seen from results obtained when air permeability measurements were carried out, this observation could not be concluded on Future researches which will consider a bigger test sample was recommended for better understanding of the effect of insulation on air permeability properties.

With CLT already a popular construction material because of its many advantages, the result could be made available to design Engineers who are interested in exposing timber to indoor environmental conditions in which the timber would be the airtight layer of the building envelope. This research clearly emphasizes the need to keep initial MC of CLT panels as designed and should be made to avoid contact with water during construction as this may affect negatively the air leakage performance of the building during service.

Just like every other construction material, timber also has its technicalities that necessitates further researches to be carried out for better air leakage performance. A future research on air permeability measurements in connections of CLT building element is recommended as the sealing was one of the problem encountered in this research. More so, the future research on the air permeability properties of the CLT wall assembly is required in larger scale test walls as insulation is a big part of buildings in Estonia and Europe in general.

SUMMARY

In this research, air permeability test was carried out on 12 different test walls with CLT as the airtight layer exposed to indoor atmospheric condition. Test walls were produced with different technologies with the main difference in the initial MC of CLT panel and the insulation material. The reason for producing test walls with different technologies was to be able to achieve the set objective which is to determine if the moisture dry out of CLT panels in test wall, different insulation solutions and indoor atmospheric conditions will affect the air permeability properties of the test wall itself, during service.

Air leakage was observed in all test walls measured and factors that were observed to have influenced air leakages includes existing atmospheric condition and initial moisture content of the CLT panel. A decrease in average RH led to test walls having bigger air leakage and vice versa. Test walls with higher initial moisture content in CLT panels were seen to have bigger air leakage compared to test walls with smaller initial moisture content in CLT panels. The effect of insulation could not be ascertained as air leakage results obtained were not sufficient enough for analysing its effect. A bigger test wall sample is recommended in the form of future studies for a better understanding of the effect of insulating material on the air leakage performance of CLT

The result obtained in this research proves to us why it’s important to ensure timbers (serving the purpose of an airtight layer in a building envelope) do not come in contact with water during construction or while transporting them as this may lead to bigger air leakage during service. Adhesives sealing tapes and polyurethane foams utilised as the sealants for elements connections in this research was also observed not to be fully airtight which has necessitated the need for further improved research to be done.

KOKKUVÕTE

Antud lõputöö raames teostati õhupidavuse katse 12-le erinevale katseseinale, kus ristkihtliimpuitpaneel seina õhupidava kihina oli avatud sisekliima tingimustele. Katseseinad ehitati erinevate lahendustega, milledeks oli erinev algne niiskussisaldus paneelides ja erinev soojusisolatsiooni materjali. Erinevate katseseinte lahenduste kasutamise põhjuseks oli uurimistöös püstitatud eesmärk, milleks oli määratleda ristkihtliimpuitpaneeli liigniiskuse välja kuvamise, erinevate omadustega soojusisolatsiooni materjali ja sisekliima tingimuste mõju välispiirde õhupidavuse omadustele kasutusea vältel.

Katse käigus jälgiti ja mõõdeti pidevalt sisekliima tingimusi ja algne ritkihtliimpuidu niiskussisaldus mõõdeti enne katse algust. Mõõtetulemustena leiti, et õhuleke esines kõigis katseseintes. Sisekliima pikaajalisem suhtelise õhuniiskuse vähenemine viis katseseinte õhulekete kasvamisele and vastupidi. Suurema algniiskusega ristkihtpaneelidest katseseintel esines märgatavalt suuremad õhulekked kui väiksema algniiskusega paneelidest seintel. Soojusisolatsiooni materjali mõju katseseinte õhupidavuse omadustele ei olnud võimalik katsetulemuste põhjal hinnata suure määramatuse tõttu. Isolatsiooni materjalide mõju leidmiseks tulevastes uuringutes on soovitatav kasutada suuremate mõõtmetega katseseinad vähendamaks soojustuse paigaldusega seotud määramatusi.

Antud magistritöö käigus saadud tulemused tõestasid miks on oluline tagada, et puitkonstruktsioonid (mis täidavad hoone piirdes ka õhupidava kihi rolli) ei puutuks kokku ehituse või transpordi käigus liigniiskuse ja veega, mis võib põhjustada suuri õhulekkeid läbi kuivamise deformatsioonide konstruktsioonide pinnal. Tulemuste põhjal samuti selgus, et aurutõkke teibi ja polüuretaanist ehitusvahu kasutamine ristkihtpaneelidest elementide omavaheline tihendamine ei taga piirde õhupidavuse ja täiendavad uuringud on vajalikud täiustatud lahenduste jaoks.

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APPENDICES

Appendix 1 Architectural drawings

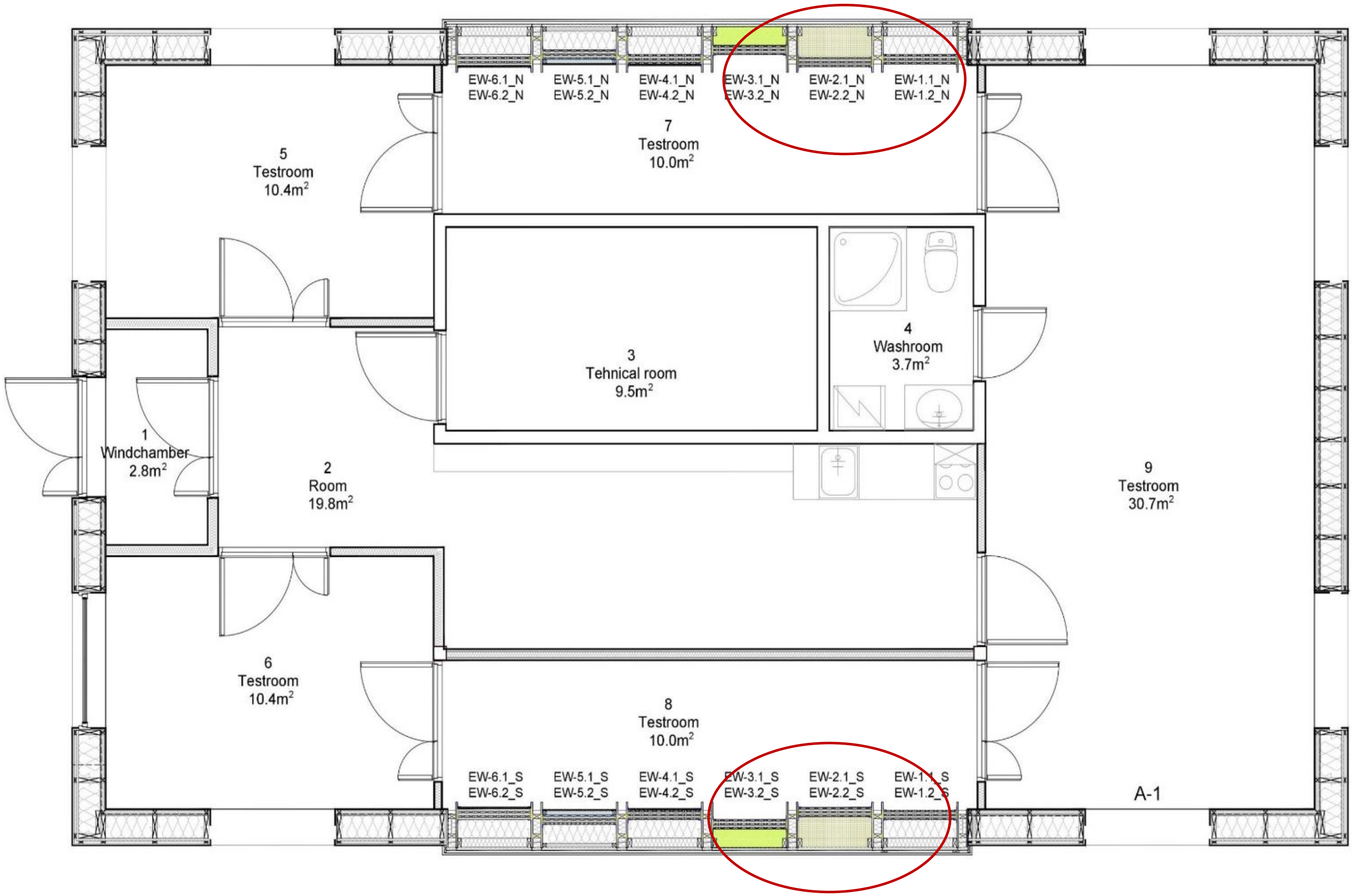

Figure A.1: *Architectural drawing of the nZEB technological test facility with red oval circle showing test walls for research (Technical drawing by Villu Kukk adjusted by the author).*